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Fire refugia in forest ecosystems of the Pacific Northwest, USA: Science and applications for conservation, adaptation, and stewardship

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Abstract

Concepts and models of fire refugia are increasingly important components of forest management and adaptation discussions in the context of wildland fire, forest and habitat conservation, and global change. Recent stand-replacing fires in mature and old-growth forests of the Pacific Northwest (PNW) region of the western United States have increased land manager and scientific interest in fire refugia that can provide important ecosystem services. Here we provide an overview of fire refugia concepts and products being actively developed and applied in forests of the PNW (Washington, Oregon, California), characterize key distinctions among fire refugia in different biophysical settings, present three case studies to illustrate applications, and briefly describe future directions for these concepts in scientist-practitioner partnerships. By increasing awareness of fire refugia concepts, datasets, and decision support tools, we aim to bolster the adaptive capacity of practitioners, managers, and partners invested in ecosystem management, while strengthening the long-horizon collaborations necessary for applied science and conservation.

KEYWORDS

adaptation, adaptive management, climate refugia, fire refugia, holdouts, mature and old-growth forests, Pacific Northwest, pyrogeography, wildfire

1 | INTRODUCTION

Concepts and models of fire refugia are increasingly a part of forest management and adaptation discussions in the context of wildland fire, forest and habitat conservation, and global change. Fire refugia are locations that burn at low severity or remain unburned, or burn less frequently, contributing critical heterogeneity to forest

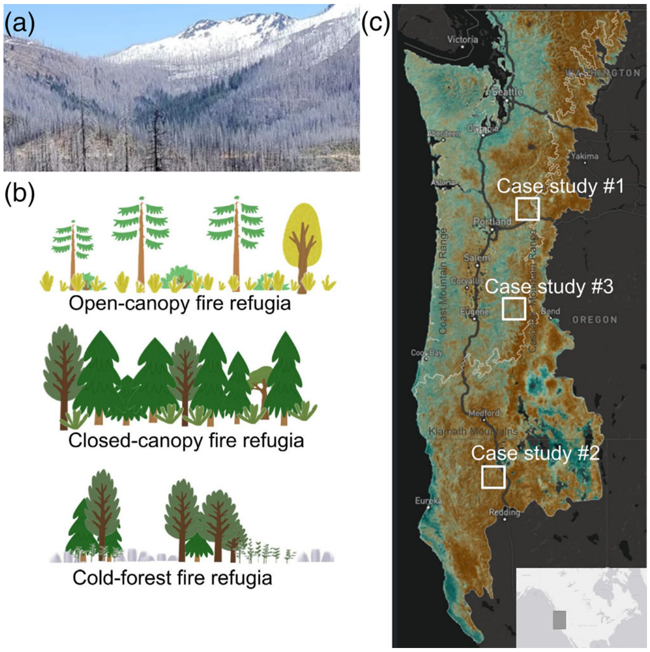

FIGURE 1 Fire refugia are locations that burn at lower severity, avoiding fire in the canopy; a typical expression of fire refugia is the legacy of green trees contrasting those killed or top-killed by stand replacing fire. (a) Fire refugia in the 2020 Slater Fire in northern California, where fire burned under extreme conditions and left very little of the forest landscape without high-severity fire effects. The low slope position and concave terrain suggest topography and related biophysical setting mediated fire behavior and supported the persistence of standing live trees. (b) Cartoon diagrams illustrating three fire refugia typologies: Open-canopy fire refugia, closed-canopy fire refugia, and cold-forest fire refugia; tree symbols loosely represent different species and functional types. (c) A map of the Pacific Northwest study region illustrating the holistic fire refugia map surface hosted in the Eco-Vis web viewer. This tool provides users with "pan, zoom, and download" capacity to examine mapped predicted scenarios based on low, moderate, and extreme fire weather conditions and ability to explore underlying drivers of predicted probability of fire refugia (https://firerefugia.forestry.oregonstate.edu/ecovis). The location of our three Case Studies are illustrated to provide geographic context for the work.

ecosystems (Figure 1; Krawchuk et al., 2020; Mackey et al., 2021; Meddens et al., 2018; Rodman et al., 2023; Talucci et al., 2022) and are related to concepts of climate-change refugia (Keppel et al., 2024; Morelli et al., 2016; Morelli, Mozelewski et al. n.d. this issue). Fire refugia support a variety of ecosystem functions including recruiting and sustaining older forests, providing habitat for wildlife, maintaining shaded micro-climates, and contributing seed sources that facilitate post-fire recovery of surrounding landscapes.

Recent high-severity fire effects in mature and old-growth forests of the Pacific Northwest (PNW) region of the western United States have increased land manager and scientific interest in fire refugia that support important ecological legacies during a time of rapid change. Fire refugia can be stochastic or relatively predictable, and fire refugia can be ephemeral or persistent, depending on whether they function as refugia consistently over time through multiple fire events (Mackey et al., 2021; Meddens et al., 2018). Predictability and persistence in fire refugia are influenced by topographic factors, vegetation and fuels, fire weather, and fire behavior—through local factors and landscape context (Downing et al., 2021; Rodman et al., 2023). In our work, we aim to leverage the predictive features of fire refugia to inform planning decisions and forest management, while recognizing that the complexities of fire behavior require a probabilistic approach—for example, considering higher and lower chances of supporting fire refugia at any given location based on predictive capacity from its biophysical setting. However, translating or "socializing" these new science and data products to inform management decisions can be challenging.

Here we provide an overview of fire refugia concepts and products being actively developed and applied to management in forests of the PNW (Washington, Oregon, California; Figure 1). We characterize some key distinctions between fire refugia in moist, dry, and cold forest settings, introduce three types of fire refugia (open-canopy, closed-canopy, and cold-forest fire refugia), present three case studies to illustrate applications, and describe future directions for these concepts in land stewardship and scientist-practitioner partnerships. Our case studies are real-world applications illustrating emerging uses of fire refugia science across the region. Our goal is to raise awareness of fire refugia concepts and data products, demonstrating that in an ever-changing landscape and policy environment, fire refugia represent areas of relative stability, or "holdouts" (Hannah et al., 2014) increasingly important to conserving biodiversity values while adapting to future conditions.

2 | BACKGROUND ON FIRE REFUGIA IN FOREST ECOSYSTEMS OF THE PACIFIC NORTHWEST

2.1 | Geography matters: key distinctions for fire refugia in moist, dry, and cold forest types

The PNW region is characterized by diverse forest types associated with geographic gradients of climate, topography, and disturbance regimes (Reilly et al., 2021; Spies et al., 2018). Maritime climates and moist, closed-canopy forests characterize much of the northwestern portion of the region, including the Coast and Cascade Mountain Ranges of Washington and Oregon. Characteristic tree species include coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*), western redcedar (*Thuja plicata*), and western hemlock (*Tsuga heterophylla*), with Sitka spruce (*Picea sitchensis*) prominent in the Coast Range maritime fog belt. To the east, over the crest of the Cascade Range, dry and moist mixed-conifer forests of ponderosa pine (*Pinus ponderosa*), interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), western larch (*Larix occidentalis*), grand fir (*Abies grandis*), and lodgepole pine (*Pinus contorta* var. *latifolia*) predominate in lower to middle elevations. Upper elevation cold forests including Pacific silver fir (*A. amabilis*), mountain hemlock (*Tsuga mertensiana*), subalpine fir (*A. lasiocarpa*), Engelmann spruce (*Picea engelmannii*), lodgepole pine, and whitebark pine (*Pinus albicaulis*) cover the higher elevations of most mountain ranges in the PNW, characterized by relatively colder temperatures and extended seasonal snowpack during winter months. To the south, the region transitions to the Klamath Mountains ecoregion with a strong west-east precipitation gradient from maritime effects and coastal fog to a summer-dry Mediterranean climate. Common forest types include species-rich mixed-evergreen and mixed-conifer zones where oaks (*Quercus kelloggii*, *Q. chrysolepis*), tanoak (*Notholithocarpus densiflorus*), Pacific madrone (*Arbutus menziesii*), incense-cedar (*Calocedrus decurrens*), sugar pine (*Pinus lambertiana*), and white fir (*A. concolor*) co-mingle with coast Douglas-fir and ponderosa pine (Franklin & Dyrness, 1988). At upper elevations, white fir and red fir (*Abies magnifica var. shastensis*) forest types are common. In the eastern Klamath ecoregion, closed- and open-canopy dry forests interdigitate depending on local climate and topoedaphic setting. Shrub-dominated communities are prominent throughout much of the Klamath ecoregion, especially in areas of serpentine bedrock and in the footprints of recent, large patches of high-severity fire, particularly in the mixed-evergreen zone. The moist, dry, and cold forest types of the region each include tree communities with differing fire regime adaptive traits (Stevens et al., 2020), characteristic historical fire regimes, and forest structures (Spies et al., 2018) that influence the variability of fire refugia across the region.

Understanding the variety of fire refugia types and their drivers is fundamental for recognizing appropriate fire refugia management strategies to employ for maintaining and improving forest resistance, resilience, and adaptation. Here, we consider three main types: open-canopy, closed-canopy, and cold-forest fire refugia (Figure 1).

Open-canopy fire refugia are exemplified by the dry mixed-conifer and ponderosa pine forests east of the Cascade crest, where frequent fire historically consumed surface and ladder fuels and maintained lower canopy cover and open old-tree forest conditions, promoting fine-scale fire refugia comprised of individual trees or small tree clusters and widespread refugia from high-severity fire across much of the landscape (Hagmann et al., 2021; Youngblood et al., 2004). Fire exclusion and selective logging of large trees have had profound impacts on these landscapes by increasing the density of small, fire-sensitive trees and horizontal and vertical fuel connectivity (Hagmann et al., 2021; Stephens et al., 2020), diminishing open-canopy fire refugia capacity across much of the region. Ongoing restoration activities in these landscapes, through mechanical fuels treatments, prescribed fire, and beneficial wildfire, aim to redevelop open-canopy fire refugia conditions in dry forest settings supporting key ecosystem elements like legacy pines (e.g., Meigs et al., 2025).

Closed-canopy fire refugia are supported by the interrelated, dampening effects that microclimate (Chen et al., 1993), vegetation traits including large tree size, thick bark, self-pruning (Stevens et al., 2020), and topographic position have on fire behavior (Pyne et al., 1996). Important examples of closed-canopy fire refugia in the region are found in Douglas-fir/western hemlock forests (Camp et al., 1997; Meigs & Krawchuk, 2018), however, it is important to recognize that location and condition matter, such that topographic context and conditions of any particular forest stand will affect its refugia capacity.

Representing a third, distinct type, cold-forest fire refugia occur at higher elevations and northerly locations, embedded in forest types with a history of less frequent, higher-severity fire, where thinner-barked fire-sensitive tree species and intense fire behavior result in limited opportunities for fire refugia during most fire events (Krawchuk et al., 2016; Naficy et al., 2021). Cold-forest fire refugia rely on fuel breaks (natural or human-made), topographic protection (Rogeau et al., 2018), and locations where cold temperatures and moist conditions can diminish fire behavior and provide refugial environments. Further work is required to characterize and quantify different types of fire refugia.

The following illustrates our thinking on the geography of closed-canopy fire refugia across dry and moist forest landscapes, as an example of the patterns we have described above.

> In drier forest landscapes, closed-canopy fire refugia are typically concentrated in topographically sheltered drainages and riparian zones, where complex,

dissected terrain and topographic shading result in moister site conditions (Aguilar et al., 2010). In these settings, lower topographic positions support higher soil moistures that ameliorate flammability, flatter slope positions moderate fire behavior, and cold air pooling (temperature inversions) can create microclimates decoupled from upslope locations in some contexts such as in the Klamath Mountains ecoregion (Downing et al., 2021; Estes et al., 2017). Closed-canopy fire refugia can also occur in patches of moist forest or elevational bands nested within a dry forest landscape matrix, where microclimatic, vegetation, and terrain influence fire behavior and effects.

In moister forest landscapes, such as the Coast Mountains and much of the Cascade Range, the role of topographic features in supporting microclimatic and vegetation conditions conducive to closed-canopy fire refugia is less prominent than in hotter and drier environments. In these moist forest landscapes, the topo-climatic setting that supports closed-canopy fire refugia extends over a larger part of the landscape and is further reinforced by microclimate and vegetation/fuel traits derived from stand conditions. However, exposure to extreme fire weather conditions becomes a major limitation to the persistence of fire refugia, and topographic features provide an important template for closed-canopy fire refugia in these extreme conditions.

2.2 | Concepts and data: Holistic fire refugia and topo-climatic fire refugia

Research on fire refugia in PNW forests has demonstrated predictable, yet complex, drivers of wildfire severity using a variety of methods anchored in a probabilistic framework. Two regional products developed using contemporary remotely sensed data from recent fire footprints include: (1) the holistic fire refugia model suite (Naficy et al., 2021), and (2) the topo-climatic fire refugia model (Appendix S1; see Krawchuk et al., 2023 for details). Note that these products do not explicitly assess persistence through multiple fire events, but key explanatory variables are consistent with analyses of persistent fire refugia demonstrated by Downing et al. (2021). The two data products can be considered "coarse filter" conservation models and maps for project-level and regional planning, for example, to identify potential fire refugia for mature and old forest assessments (e.g., USFS, 2024a). Ongoing studies of fire refugia using "fine filter" species-level approaches, such as fire refugia for the northern spotted owl (NSO; *Strix occidentalis caurina*) habitat, provide additional spatial understanding for wildlife applications.

The holistic fire refugia concept and models (Krawchuk et al., 2023; Naficy et al., 2021) were developed to quantify the relative probability of fire refugia across a broad region of the PNW. Holistic fire refugia models use explanatory variables representing topography, fire weather, fuels and vegetation, and fire growth following an evolution of these ideas illustrated in Meigs et al. (2020) and Downing et al. (2021); explanatory variables are described in Appendix S1, for reference. In addition to models of fire refugia, Naficy et al. (2021) also developed models for moderate- and high-severity fire. All models were developed at a 30-m resolution using Landsat data to characterize burn severity, where fire refugia pixels were identified as those with <10% fire-caused basal area mortality, based on field calibrations from Reilly et al. (2017). Because the models include dynamic variables of daily fire weather (relationships to relative humidity and maximum daily temperature in the models) and fire growth, a user is required to specify these conditions to produce predictive maps showing a relative probability of fire refugia occurrence (i.e., the probability of fire refugia, given a fire occurs). The fire refugia website and Eco-Vis web viewer (Krawchuk, 2025; Naficy et al., 2021; Figure 1) host predicted maps for fire weather scenarios including low (10th percentile of weather conditions, e.g., relative humidity, maximum temperature), moderate (50th percentile), and high (90th percentile) for generating fire refugia probability, and serves as a portal for data access and outreach materials. High fire weather conditions and high fire growth scenarios enable evaluation of fire refugia persistence under expected hotter-drier future climate and more extreme fire spread conditions. The Eco-Vis web viewer also provides interpretative graphics that illustrate the relationships between explanatory variables and fire refugia probability, allowing users to explore concepts as they relate to different types of fire refugia (e.g., closed-canopy, open-canopy, cold-forest fire refugia).

The topo-climatic fire refugia concept and models were developed to quantify the probability of potential fire refugia across the region using a longer-term climatological approach. The topo-climatic model integrates the "normal fire environment," an estimate of fire occurrence using recent historical climatological (1991–2020) normals (Davis et al., 2017), with four topographic predictors of fire refugia as explanatory variables (Appendix S1). The topo-climatic fire refugia model does not include information on vegetation or fuels as drivers of fire refugia, instead using a mask of forest-capable sites to represent the intrinsic underlying forest condition. The map products can be interpreted by overlaying them with existing forest conditions to identify, for example, opportunities for maintaining existing mature and older forest serving as fire refugia based on topo-climatic setting, as well as the opportunity to identify locations on the landscape where, for example, recruitment of mature and old, closed-canopy forest might be most successful. Climate change projections developed from the topo-climatic models identify locations most likely to persist as fire refugia given future fire environments, using climatological data to replace recent historical normals with projected values for 2031–2060 and 2071–2100 (Davis et al., 2017).

3 | CASE STUDIES

The following three case studies provide examples of different ways fire refugia map products are being considered by managers and practitioners on USDA Forest Service (USFS) administered public lands of the region. The case studies were selected from across the geography of the region (Figure 1), including examples from moist and dry forest landscapes that consider closed-canopy and open-canopy fire refugia types. Note, we do not explicitly illustrate cold-forest fire refugia in these examples. A list of additional projects where fire refugia concepts or data have been considered or integrated is listed in Table S1 in Appendix S3.

3.1 | Case study #1, Little White Salmon, Washington

The USFS Little White Salmon Forest Resiliency and Fire Risk Mitigation Project (USFS, 2024b) seeks to increase forest resilience to climate-related stressors and mitigate fire risk to highly valued resources in the Little White Salmon watershed on the Gifford Pinchot National Forest, Washington. This project area includes predominantly moist forest characteristics and closed-canopy fire refugia, transitioning to drier forest types to the east. Fire refugia were recognized as important components of a resilient landscape during project planning. The USFS project team worked together with fire refugia scientists to develop a "Manager's Brief" (Krawchuk et al., 2023) to distill information into language and framing accessible to managers. This process included multiple meetings to discuss fire refugia and potential applications for the Little White Salmon Project with USFS staff as well as the South Gifford Pinchot Collaborative that includes a diverse group of community partners.

Based on the engagement between researchers, managers, and the community, the USFS team was interested

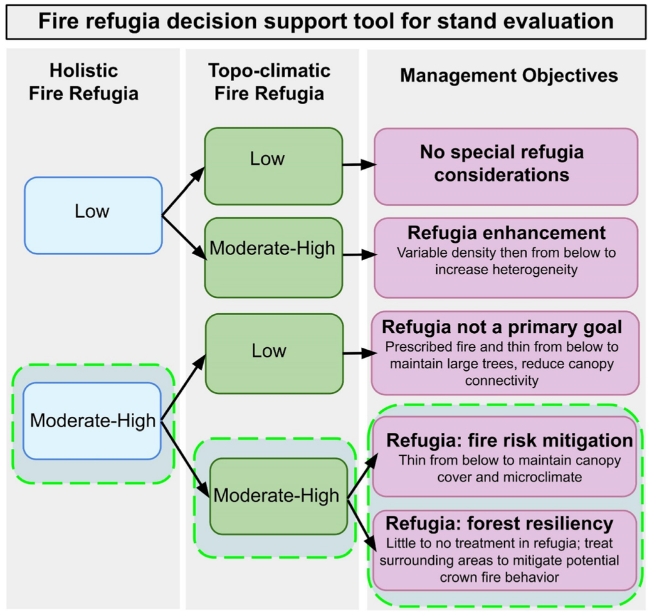

FIGURE 2 Flowchart of fire refugia datasets and management objectives showing the fire refugia decision support tool for stand evaluation presented in Case Study #1, for the Little White Salmon project on the Gifford Pinchot National Forest, Washington. The goal is to identify capacity for maintaining or enhancing "persistent" fire refugia, defined for this project as areas with moderate-to-high holistic fire refugia probability under a moderate fire weather scenario (50th%-ile weather conditions), and moderate-to-high current and future topo-climatic fire refugia probability (dashed green lines). In this category of "persistent" fire refugia capacity, management objectives varied depending on whether locations were prioritized for fire risk mitigation versus forest resiliency-biodiversity desired conditions.

in developing a method for integrating multiple fire refugia products (fire refugia templates) to support decisions for maintaining or enhancing "persistent" fire refugia in the project area. Here, persistent fire refugia were defined as areas with moderate-to-high holistic fire refugia probabilities under a moderate fire weather scenario (representing *current* refugia capacity) and moderate-to-high current and future topo-climatic refugia probabilities (including *future* capacity; Figure 2). Management recommendations for each stand in the project were then evaluated based on holistic and topo-climatic refugia probabilities, as illustrated in the decision support tool in Figure 2. For stands identified with persistent fire refugia capacity, management objectives were evaluated as either: (1) refugia fire risk mitigation or (2) refugia forest resiliency, depending on their context and a priority toward reducing fire hazard to nearby communities versus enhancing forest resilience, respectively. Refugia fire risk mitigation actions included thinning from below to maintain canopy cover and microclimate, with the goal of interrupting fire flow. Refugia forest resiliency actions included little to no treatment in refugia and treating surrounding areas to mitigate the risk of crown fire exposure, with the goal of increased forest resiliency and prioritizing biodiversity. Stands with low holistic and moderate-high topo-climatic fire refugia probability were identified for refugia enhancement (variable density thinning from below to increase heterogeneity; Figure 2), whereas those with low probability of any refugia were afforded no special refugia considerations.

Integrating the fire refugia decision tree into the Little White Salmon vegetation management project served as a screening tool for the proposed actions and provided additional rationale to support and discuss silvicultural activities in forested stands. Overall, the project provided opportunities for management partners and scientists to work together to identify how a variety of refugia products might aid decision making. The Manager's Brief (Krawchuk et al., 2023) developed through this collaboration includes a list of "frequently asked questions" for land managers related to common management concerns in the region and how fire refugia data might be leveraged in that context, to support building a fire refugia community of practice.

3.2 | Case study #2 South Fork Sacramento, California

In historically frequent-fire regimes with complex topography like the Klamath Mountains ecoregion of southwest Oregon and northwest California, frequent, low- and mixed-severity fires maintained a resilient landscape mosaic resulting from interactions between topography, vegetation, and weather (Perry et al., 2011). This fire regime was a major determinant of the heterogeneous landscape, including persistent closed-canopy fire refugia, likely restricted to topographically sheltered locations (e.g., Downing et al., 2021) with decoupled microclimates and large, older trees (Davis et al., 2019; Frey et al., 2016), embedded in a landscape mosaic of younger seral stages and other vegetation types such as prairie, pine-oak woodland, and shrubland-chaparral. This pattern likely provided optimal habitat for the northern spotted owl (NSO) in the southern part of its range because the NSO nests and roosts in closed-canopy, older forests (nesting and roosting [NR] forest) and forages along ecotones between older forests and younger seral stages (Ward & Noon, 1998; Zabel et al., 1995). In the more mesic portions of the Klamath ecoregion, recent research (Knight et al., 2020) indicates that over a century of fire exclusion has contributed to the expansion of Douglas-fir forest, potentially creating so-called "fire-excluded nesting-roosting (NR)" forest in uncharacteristic locations (e.g., Lesmeister et al., 2025). At the same time, much of the historical NR forest was clear-cut logged and planted and is currently unsuitable to NSO for nesting and roosting. These younger forests, including plantations and fire-excluded forest, can increase fire hazard across the landscape (e.g., Countryman, 1956; Hessburg et al., 2021; Zald & Dunn, 2018).

Land managers now face a conservation conundrum between longer-term landscape restoration versus a shorter-term single species focus for NSO. Do managers actively restore 'fire-excluded NR' forests to a more open condition to increase forest resilience and support additional foraging habitat that may improve territory fitness for NSO (Franklin et al., 2000), but with the implication of removing perceived NR forest for this critically imperiled species? Or do they retain these patches of "fire-excluded NR" forest in uncharacteristic locations (sensu Camp et al., 1997 "apparent fire refugia") to maximize current NR forest and yet risk greater losses of characteristic long-term "persistent" NR forest when fire returns to the landscape? Whether restoring "fire-excluded NR" forest to more open conditions should be considered an actual loss of NR forest versus a realignment to historical conditions is debatable, but research suggests that some fire-excluded landscapes currently have, and are being managed for, greater amounts of NR forest than what was maintained historically by active fire regimes, including Indigenous burning (Halofsky et al., 2024; Knight et al., 2020).

The USFS South Fork Sacramento Public Safety and Forest Restoration Project (USFS, 2024c) is located in the easternmost portion of the Klamath ecoregion on the Shasta-Trinity National Forest near the city of Mount Shasta, California. The area contains popular recreation sites and forests inhabited by NSO, some of which are "fire-excluded NR" forest. Current and future projected increases in wildfire activity are raising concerns for public safety and forest resource conservation and were the impetus for the development of this project. The project area historically contained a mosaic of forest types including closed-canopy NR in fire refugia, but timber harvest has removed many areas of high-quality NR forest, and fire exclusion has allowed the expansion of NR forest into historically drier and more open forest and cover types, for example, pine-oak woodlands.

The USFS planning team developed a management alternative designed with fire refugia concepts and data to target the locations of silvicultural prescriptions. The team identified locations that included: persistent NSO habitat (defined here as maintaining suitable mapped

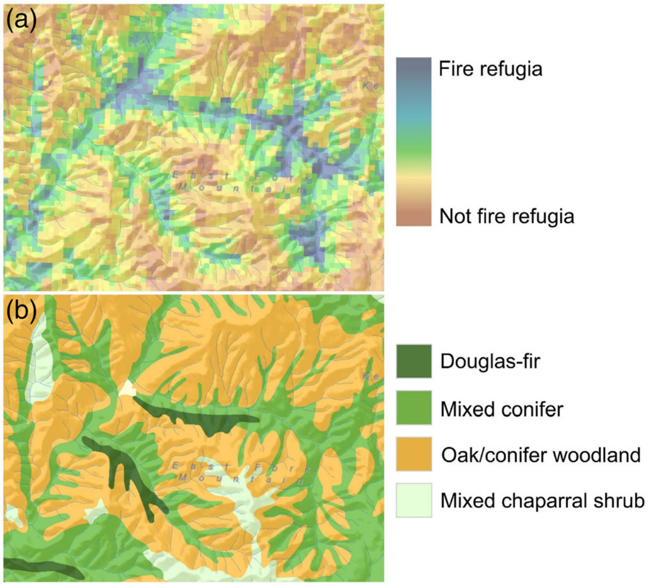

FIGURE 3 The alignment of fire refugia and historic Douglas-fir and mixed-conifer vegetation for an area located at East Fork Mountain of the Shasta-Trinity National Forest in northern California, illustrating the concept of fire refugia data guiding management for persistent closed-canopy fire refugia as habitat for northern spotted owl in dry forest settings (Case Study #2). (a) Map of fire refugia capacity showing relationships to topography and streams using a combined layer integrating holistic and topo-climatic fire refugia predictions. (b) Historical vegetation mapped from the early 20th century illustrating forest landscape patterns prior to fire exclusion. The area shown is approximately 25 miles southeast of the planning area for the South Fork Sacramento project; no historic vegetation GIS layers exist for the planning area. Data source for map b is from http://vtm.berkeley.edu/#/data/vegetaton (Kelly et al., 2005).

NSO habitat for at least three decades, based on a combination of nesting, roosting, and foraging forest types; Glenn et al., 2017), interior NR forest less prone to burning at high severity (Davis et al., 2022; Lesmeister et al., 2021), and high fire refugia capacity (using a combination of holistic and topo-climatic fire refugia data; Figure 3). Locations meeting these three criteria were designated for minimal impact, or "light touch" vegetation management, to maintain suitable NSO NR habitat (USFS, 2024c). Outside these areas, vegetation management goals focused on restoring historical open forest pine-oak woodlands, supporting NSO prey habitat, and reducing contagion of stand-replacing fire behavior. This case study illustrates the use of fire refugia concepts and data to support controversial management decisions related to fire risk mitigation and conservation of species listed under the Endangered Species Act (ESA, 1973). Lesmeister et al. (2025) describe these refugia-based approaches in more detail.

3.3 | Case study #3, Lookout Fire, H.J. Andrews experimental forest and long-term ecological research site, Oregon

This case study illustrates an evaluation of fire refugia model predictions that is important for building trust, acceptance, and understanding for management applications. As illustrated in case studies #1 and #2, land managers are beginning to use fire refugia products for decision making. However, how good are these models developed from previous fires at predicting fire refugia in subsequent fire events, and can managers sufficiently rely on this information to guide decision-making for resource management? The H.J. Andrews Experimental Forest and Long-Term Ecological Research site (HJA) within the USFS Willamette National Forest in the Western Cascades of Oregon has been a hub for science-management partnerships aimed at better understanding the ecology and management of moist, temperate coniferous forests for more than 75 years. In summer 2023, the 10,422-ha Lookout Fire burned 68% of the HJA footprint with mixed-severity fire effects, including patches of fire refugia (low severity or unburned) as well as moderate- and high-severity fire (Box 1, Figure 4a). The fire provided a valuable opportunity to compare spatial patterns of the observed fire severity (measured as estimated basal area mortality) to maps of predicted holistic fire refugia developed from previous fires.

We used the holistic fire refugia model to predict probabilities of fire refugia for the Lookout Fire based on fire weather from the event itself, tailoring the probabilities to phases of observed weather conditions throughout the fire (Box 1, Figure 4b,c). These tailored probabilities differ from available "off-the-shelf" scenarios (Figure 4d) where mapped predictions show probabilities of fire refugia for specified low, moderate, or extreme conditions across the entire footprint of the area of interest. The tailored mapping illustrated in Box 1 provides an important opportunity to test observed versus predicted fire effects (Figure 4e) and to evaluate differences from what was expected for an individual fire where the fire progression was tracked and reported very closely due to the HJA's classification as a high value resource. The analysis shows that observed patterns of fire severity generally align with predicted values of fire refugia, though with a fair degree of variability.

Focal research areas like the HJA and detailed study of individual fires can help determine gaps in our understanding of the factors controlling fire refugia and high-severity fire. At the HJA, documentation of fire management actions and impacts are being cataloged and archived and will provide valuable cross-references to fire refugia predictions for a deeper understanding of locations

BOX 1 Fire refugia model predictions versus reality.

The variability in observed severity on the Lookout Fire located near Blue River, OR, including the H.J. Andrews Experimental Forest, provides an important opportunity to learn how well fire refugia models perform and consider factors influencing discrepancies, in a landscape dominated by moist forest types, with cold forests at higher elevations. The observed patterns of burn severity (Figure 4a) generally aligned with predicted values of fire refugia based on observed weather conditions, although substantial variability in these relationships remained (Figure 4e); see Appendix S2 for additional maps and details. Fire weather classifications were used to tailor the predictions based on observed conditions (Figure 4b) by stitching together predictions of fire refugia from 10th, 50th, and 90th percentile scenarios (Figure 4c) identified by analyzing daily weather from the Lookout Fire (Appendix S2). Variability in observed severity decreased as probabilities of holistic fire refugia approached one (Figure 4e), suggesting the most reliable predictive features are associated with lowest tree mortality.

The two large high-severity patches observed from the Lookout Fire (Figure 4a) included areas predicted to have high fire refugia capacity (Figure 4c,d), suggesting that managers using these products should consider the potential causes of such disagreements as a foundation for realistic expectations. For example, fire refugia models capture the general probability of fire effects given vegetation, terrain, and fire weather/fire growth, but do not integrate fire operations and decision-making or stochastic events such as fine-scale meteorological events and cannot include all processes. Fire management influences fire behavior and effects through suppression operations such as firing (i.e., applying fire to consume fuels intentionally) and creation of fire line (e.g., felling trees, implementing fuel breaks with bulldozers), as well as strategic responses that reduce firefighter risk by containing wildfire in large landscape units (Dunn et al., 2020). Fire effects are also influenced by idiosyncratic weather and fire behavior, such as a localized microburst documented on the Lookout Fire that pushed fire through the old-growth forest stands resulting in extensive high-severity fire effects in locations where fire refugia were expected. Such fine-scale meteorological events are not captured in daily fire weather estimates used for our tailored prediction or in model fitting, but will be important for the next steps of evaluating fire refugia model applicability and uncertainty, and continued model development.

where observed fire effects do and do not align with model predictions. Overall, the HJA-Lookout Fire case study illustrates that models developed to predict fire refugia serve as useful guides for future fire effects; the models do not predict perfectly, and that is not their purpose. Examining the outcomes of fire events in the context of fire refugia provides the opportunity for conversations to build trust with managers who rightfully ask, "how well do the models perform in predicting, planning, and prioritization related to future fires?"

4 | NEXT STEPS: FUTURE OF FIRE REFUGIA RESEARCH AND PARTNERSHIPS BETWEEN SCIENTISTS AND PRACTITIONERS NEEDED FOR INTEGRATING THE "SO WHAT?" OF SCIENCE INTO FOREST STEWARDSHIP

Our case studies illustrate three different ways in which fire refugia concepts and datasets are informing conservation and management of forest ecosystems. Fire refugia are one component of the climate-change refugia conservation cycle (Morelli, Mozelewski et al. n.d. this issue) and are critical to climate-change refugia frameworks (Keppel et al., 2024; Rodman et al., 2023) that integrate multiple processes together to provide decision support for biodiversity conservation and adaptation. Ongoing development of fire refugia products to refine the integration of climate- change forecasting will be critical to these frameworks. Moving forward, fire refugia maps and concepts could be leveraged in regional conservation planning efforts to identify locations of high conservation significance and connectedness due to their fire refugia and climate refugia status (see e.g., Table S1 in Appendix S3). A critical next step to

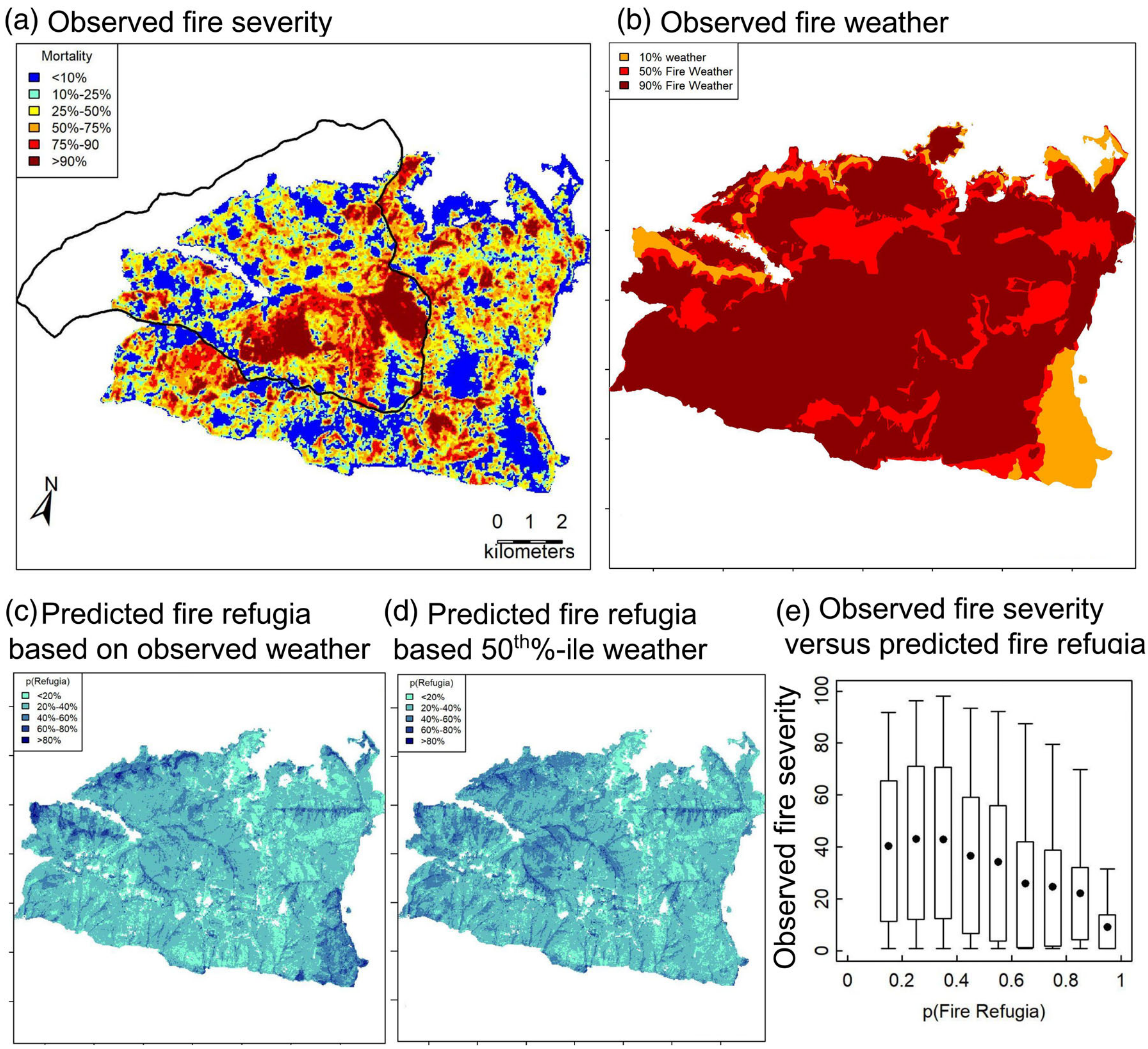

FIGURE 4 Fire refugia maps and data from Case Study #3 Lookout Fire across the H.J. Andrews Experimental Forest (HJA) in the western Cascades of Oregon. (a) The observed fire severity mosaic from the Lookout Fire showing the outline of the HJA in black. Patches of fire refugia (<10% basal area mortality) are illustrated in dark blue. (b) Fire weather scenarios developed from phases of observed fire weather conditions on the Lookout Fire; see Appendix S2 for details on the development of the three fire weather scenarios. (c) A map of the probability of fire refugia, p(Refugia), predicted based on the observed three scenarios of fire weather, demonstrating a tailored spatial mosaic of predictions. In comparison, (d) shows a map of the probability of fire refugia predicated from a 50th percentile scenario of fire weather "off the shelf" from the Eco-Vis website and data distribution. (e) Quantitative comparison of observed fire severity (*y*-axis, represented as % basal area mortality) and probability of fire refugia (*x*-axis, p(Refugia)) from the holistic fire refugia models using estimates of observed fire weather conditions (see Appendix S2 for details), demonstrating that observed patterns of fire refugia generally align with predicted values, though with a fair degree of variability.

developing fire refugia science that is more socially and ecologically responsive involves truly transdisciplinary work, including respectful and reciprocal relationships with Tribal partners tiering to a two-eyed seeing framework (Bartlett et al., 2012) that incorporates both western science and Indigenous Knowledge. Working with Indigenous knowledge holders to understand knowledges, practices, and belief systems related to concepts of fire refugia could provide important guidance for ecocultural restoration. For example, Tribal members and cultural fire stewards Azzuz and Robbins from the Yurok Tribe in the Klamath ecoregion indicate, "there's a specific area that they're [Douglas-firs] supposed to be in and we used fire to maintain that balance" (Azzuz & Robbins, 2025); this statement aligns with concepts described in our Case Study #2. Continued co-production with managers, practitioners, and knowledge keepers is critical to further improve the refugia toolbox to meet our responsibility as researchers (Lubchenco, 1998) to provide science to inform and support policy and management decisions.

As a diverse group of researchers and managers, we have invested in working with fire refugia concepts and data because of the scientific insights they provide and the important management applications that extend from the science. We have been engaged in this translational science (Enquist et al., 2017) with a wide range of people and projects in the region to include concepts of fire refugia (Table S1 in Appendix S3). However, as a group, we also recognize the challenges of socializing new concepts and data into the decision space of managers, where there is often limited bandwidth to effectively distill them into the core salient "so what?" conclusions they need (Hunter et al., 2020). Moreover, there is limited funding available for scientists to invest in these long-horizon collaborations that go well beyond the typical funding cycle of grants, even in the context of co-production (Glenn et al., 2022).

The progress demonstrated in our case studies resulted from trust and respect built from investing in science-manager partnerships and going the extra mile to find a comfortable space to iterate on the "so what?" Progress to date would not have been possible without insights from practitioners, managers, and partners who have a very clear understanding of hurdles on the ground, current sideboards and constraints, and what is needed to move forward with project planning, implementation, and monitoring. Our experiences working as scientists and managers with shared interests in fire refugia have highlighted the importance of building partnerships that go far beyond the typical timeframe of co-production and applied science. In this time of accelerated global change and uncertainty, it is critical to find ways to support these long-horizon partnerships, both from western science and Indigenous Knowledge perspectives. As a whole, we need to adjust our scientist-manager-stewardship cultures to fully realize adaptive management, in particular for "learning by doing" to more fully develop our understanding of climate-change refugia and fire refugia.

AUTHOR CONTRIBUTIONS

Meg A. Krawchuk: Conceptualization; writing—original draft; review; editing; visualization. **Garrett W. Meigs:** Conceptualization; writing—original draft; review; editing; visualization. **Cameron E. Naficy:** Conceptualization; writing—original draft; review; editing; visualization. **David M. Bell:** Conceptualization; writing—original draft; review; editing; visualization. **Jessica L. Hudec:** Conceptualization; writing—original draft; review; editing; visualization. **Jeremy T. Rockweit:** Conceptualization; writing—original draft; review; editing; visualization. **Raymond J. Davis:** Conceptualization; writing—original draft; review; editing; visualization.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data used in this article are available from the corresponding author upon request. Data download is available from web portals cited in the text.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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