North *et al. Fire Ecology* (2024) 20:50
https://doi.org/10.1186/s42408-024-00282-y

Fire Ecology

FORUM

Open Access

Strategic fire zones are essential to wildfire risk reduction in the Western United States

Malcolm P. North[1*], Sarah M. Bisbing[2], Don L. Hankins[3], Paul F. Hessburg[4], Matthew D. Hurteau[5], Leda N. Kobziar[6], Marc D. Meyer[7], Allison E. Rhea[8], Scott L. Stephens[9] and Camille S. Stevens-Rumann[8]

Abstract

Background Over the last four decades, wildfires in forests of the continental western United States have significantly increased in both size and severity after more than a century of fire suppression and exclusion. Many of these forests historically experienced frequent fire and were fuel limited. To date, fuel reduction treatments have been small and too widely dispersed to have impacted this trend. Currently new land management plans are being developed on most of the 154 National Forests that will guide and support on the ground management practices for the next 15–20 years.

Results During plan development, we recommend that Strategic Fire Zones (SFZs) be identified in large blocks (≥ 2,000 ha) of Federal forest lands, buffered (≥ 1–2.4 km) from the wildland-urban interface for the reintroduction of beneficial fire. In SFZs, lightning ignitions, as well as prescribed and cultural burns, would be used to reduce fuels and restore ecosystem services. Although such Zones have been successfully established in a limited number of western National Parks and Wilderness Areas, we identify extensive remote areas in the western US (8.3–12.7 million ha), most outside of wilderness (85–88%), where they could be established. Potential wildland fire Operational Delineations or PODs would be used to identify SFZ boundaries. We outline steps to identify, implement, monitor, and communicate the use and benefits of SFZs.

Conclusions Enhancing collaboration and knowledge-sharing with Indigenous communities can play a vital role in gaining agency and public support for SFZs, and in building a narrative for how to rebuild climate-adapted fire regimes and live within them. Meaningful increases in wildland fire use could multiply the amount of beneficial fire on the landscape while reducing the risk of large wildfires and their impacts on structures and ecosystem services.

Keywords Firefighter work force, Forest resilience, Indigenous burning, Lightning-ignited fire, Prescribed fire, Wildfire smoke

Resumen

Antecedentes En las cuatro últimas décadas, los incendios de vegetación en la región continental del oeste de los EEUU se han incrementado tanto en tamaño como en severidad, luego de más de una centuria de supresión y exclusión de estos incendios. Muchos de los bosques de esta región han experimentado históricamente fuegos frecuentes y limitados por la disponibilidad de combustible. Al presente, los tratamientos de exclusión del fuego han sido pequeños en superficie y ubicados muy dispersamente en el terreno como para impactar esta tendencia incremental en cuanto al tamaño y severidad de los incendios. Los nuevos planes de manejo de tierras están siendo

*Correspondence:
Malcolm P. North
mnorth@ucdavis.edu
Full list of author information is available at the end of the article

desarrollados en la mayoría de los 154 Bosques Nacionales, los que guiarán y ejecutarán en el terreno las prácticas de manejo para los próximos 15-20 años.

Resultados Durante el desarrollo del plan, recomendamos que sean identificadas en el terreno Zonas Estratégicas de fuegos (SFZs) en grandes superficies (> 2.000 ha) de tierras federales, amortiguadas por una zona distante (> 1-2,4 km) de la interfaz urbano-rural, para la reintroducción de fuegos benéficos. En las SFZ, las igniciones por rayos, así como las quemas prescriptas y quemas culturales controladas, podrían ser usadas para reducir la carga de combustibles y restaurar servicios ecosistémicos. Aunque estas zonas han sido establecidas en un número limitado de Parques y Áreas Silvestres del oeste de los Estados Unidos, identificamos áreas remotas extensas en el oeste de los Estados Unidos (de 8,3 a 12,7 millones de ha), la mayoría por fuera de las áreas silvestres (85-88%), donde éstas podrían establecerse. Las delineaciones de áreas de incendios potenciales (PODs), podrían utilizarse para identificar los límites de las SFZs. Delineamos los pasos para identificar, implementar, monitorear, y comunicar el uso y beneficios de las zonas estratégicas de los fuegos (SFZs).

Conclusiones El aumentar la colaboración y compartir los conocimientos con comunidades indígenas pueden jugar un rol vital para ganarse el respaldo del público y de las agencias para implementar las SFZs, y en la construcción de una narrativa sobre cómo reconstruir los regímenes de fuego adaptados al clima y cómo vivir en medio de ellos. El significativo incremento en el uso del fuego en el manejo de vegetación puede multiplicar el número de fuegos beneficiosos en el paisaje y reducir al mismo tiempo el riesgo de grandes incendios y sus impactos en estructuras y servicios ecosistémicos.

Background

Western continental US forests are experiencing extreme wildfires of unprecedented size and severity. Approximately 15.5 million ha have burned (National Interagency Fire Center accessed October 30, 2023[1]) over the last five years, and Washington, Colorado, New Mexico, and California all experienced their largest recorded wildfires since 2020. Comparing 1985 to 2022, the mean annual area burned by wildfire increased by 257% (1.89 million ha) and mean annual federal suppression costs increased by 332% ($2.01 billion USD adjusted to 2020 USD) (https://www.nifc.gov/fire-information/statistics/suppression-costs, accessed September 2023).

Fuels and tree density reduction are needed in many forests to change this trend of extreme fire behavior (Hessburg et al. 2019, 2021; Prichard et al. 2021, North et al. 2022). Yet the two principal fuel and density reduction treatments, mechanical thinning and prescribed burning, have been limited in size and extent (Valiant and Reinhardt 2017) due to operational, budget, access, regulatory, and litigation barriers (Quinn-Davidson and Varner 2012; Miller et al. 2020). Recent research in California's Sierra Nevada found that the average Forest Service treatment unit was 15 ha, and that annual treated area amounted to only 10% of the estimated 252,000 ha yr^{-1} area that pre-colonial era fire regimes maintained in a fuel-limited condition (North et al. 2021).

Wildfires are currently affecting far more area than management treatments, and will continue to do so for the foreseeable future. For example, in less than 100 days in 2021, California's Sugar and Dixie fires burned more than 433,000 ha on the Plumas and Lassen National Forests, which, at recent treatment rates (i.e., 1,586 ha yr^{-1} [Coppoletta et al. 2022]) would be completed on the two National Forests by the year 2294. Although recent initiatives, such as the 2021 Infrastructure Investment and Jobs Act (Pub. Lib. # 117–58), and the 2022 Inflation Reduction Act (Pub. Lib. # 117–176), provide a temporary surge in funding to help with budget and personnel shortages, wildfire area will continue to outpace fuel reduction treated area by one or two orders of magnitude. Given the current constrained pace and scale of treatments, a new model is needed to effectively reduce future wildfire size and severity.

Increasing treatment extent with strategic fire zones

What is missing in most western US forest landscapes is a proactive designation of areas free from the obvious constraints of the wildland-urban interface (WUI), which we term Strategic Fire Zones (SFZs). In these zones, fire is expected, planned for, and leveraged to increase large landscape resilience.

Although much of the wildfire structural damage that occurs in the western US is concentrated in WUI areas, the vast majority of burn area occurs in extensive areas of backcountry forest. The size and severity patterns of these burns show that under moderate fire weather conditions, actively managing wildfires for resource benefit (i.e., "fire effects with positive value or that contribute to the attainment of organizational goals" [USDA 2014 can help restore forest ecosystems and

[1] https://www.nifc.gov/fire-information/statistics/wildfires

increase their resilience to changing climate and future wildfires (Meyer 2015; Hessburg et al. 2019). Identifying SFZs where, under the right fuel and weather conditions, fire is used for ecological and cultural benefits, would significantly increase fuel reduction pace and scale, and reduce future wildfire severity. Creation of such zones is supported by several policies and guides, including the 2012 Forest Service Planning Rule at 36 CFR § 219.8, and the 2014 National Cohesive Wildfire Management Strategy (USDA 2014, p. 32–33).

A fundamental advantage of SFZs is that fire would be dynamically managed to reduce fuels and restore a keystone ecosystem process, without needing a case-by-case evaluation, regulatory oversight, or additional environmental review. SFZs are not a new idea. Several National Parks and a few National Forest Wilderness Areas (van Wagtendonk 2007; Parks et al. 2015; Kreider et al. 2023; Jaffe et al. 2023) have used such beneficial fire for decades. However, policy changes that encouraged proactive fire application in western US forests have created only marginal increases in annual burned area (Young et al. 2020). Several recent surveys highlight the most common reasons for limited use of ecologically beneficial fire. Chief among them are a risk-averse agency culture and the perception of limited leadership support of proactive fire use (North et al. 2015b; Schultz et al. 2019; Miller et al. 2020; Williams et al. 2024).

The 2012 USFS Planning Rule (77 FR 21162) provides a means of reducing this impediment. Over the next several years, each of 154 National Forests will develop new forest plans guiding on-the-ground management practices for the next 15–20 years. Eight National Forests were identified as 'early adopters' (the first to develop new plans), and three were in California's southern Sierra Nevada, the Inyo, Sequoia, and Sierra. These National Forests adopted an analysis conducted by a Forest Service Pacific Southwest Regional Office team that identified "wildfire restoration" and "wildfire maintenance" zones in California's National Forests. In these zones, should lightning ignitions start a fire when weather and fuel moistures conditions are within a pre-determined range, the fire is managed under a non-full suppression strategy that can reestablish fire as a key ecosystem process. Any effort to suppress the wildfire requires written justification, making it clear that working with ecologically beneficial fire is supported by the three National Forests and Regional Office leadership. There is now an opportunity to identify SFZs in National Forest plans providing support for fire management officers and other decision-makers working with fire. The directives and leadership support for on-the-ground operations are codified in each National Forest's 15–20 year land management plan.

Here, we describe how the three early adopter National Forests went through this process and suggest a step-by-step approach to identifying, implementing, and communicating the benefits of SFZs (Table 1) (see Supplemental Table 1 for links to data and reports). We also conduct an analysis to determine the area and distribution of potential SFZs in the western US. Following SFZ identification, we discuss research and monitoring objectives and outreach opportunities, with particular attention to working with Indigenous communities. Other impediments may also constrain adoption of SFZs. Thus, in a final section, we examine two of the most prominent impediments, smoke management and limited work force capacity, suggesting these also provide opportunities for change.

SFZ identification and implementation

In the southern Sierra Nevada, identifying potential wildfire restoration and maintenance zones first required identifying which areas were potential candidates. Earlier analysis had classified areas in Sierra Nevada National Forests that could not be mechanically treated due to management allocation (i.e., a Congressionally designated Wilderness or roadless area), topographic and access limitations (i.e., too steep or too distant from an existing road) or administrative constraint (i.e., riparian zones, threatened and sensitive species habitats, [North et al. 2015a]) (Supplemental Table 1). To restore forest conditions and ecosystem resilience, these relatively inaccessible areas would have to be modified from their current condition with some form of beneficial fire, suggesting their potential inclusion in an SFZ.

The next step (Table 1) was to identify likely fire containment boundaries. Potential Operational Delineations (POD) boundaries were initially identified by means of a quantitative risk assessment based on characterized burn probability, fireline intensity, likely fire effects, and wildfire risk to highly valued resources and assets (Scott et al. 2013). Building on this analysis, Thompson et al. (2016) identified landscape features conducive to fire containment, and from that demarcated PODs across the area of the three early adopter National Forests.

PODs were further refined through National Forest specialist review, and input from local stakeholders and tribes. Indigenous Tribes were consulted to identify areas with cultural significance and to discuss burning practices that would protect these resources. The analysis found that beneficial fire could be used to restore and maintain conditions in 37% of PODs on the three National Forests, including many areas outside roadless and wilderness areas, yet located far from the WUI. Although approximately 1/3 of the PODs were designated for beneficial fire use or maintenance, they were remote and their size was substantial, accounting for 1.32

Table 1 Steps to identify, implement, and communicate the use and benefits of Strategic Fire Zones. Examples refer to studies that can provide guidance for each of the approaches

Process:	Objective:	Approach:	Examples:
Assessment	Identify potential areas for Strategic Fire Zones	a) Constraints on mechanical treatment necessitate restoring fire to reduce fuels b) Risk assessment c) Potential Operational Delineations d) Collaboration with Indigenous Tribes, local expertise, neighboring landowners, and stakeholders	a) North et al. 2015a b) Scott et al. 2013 c) Thompson et al. 2016, 2022a, b d) Lake et al. 2017
Project Planning	Prepare the landscape for fire	a) Pyrosilviculture approach to treat POD boundaries b) Development of cultural burning plans/projects in areas important to tribal entities	a) York et al. 2021a, b; North et al. 2021 b) Kimmerer and Lake 2001; Marks-Block et al. 2021a, b
Research & Monitoring	Evaluate ecological and social benefits and harm from fire restoration	a) Monitor effectiveness of beneficial fire (remote sensing, field plots) b) Use tools that capture heterogeneity (e.g., LiDAR) c) Document public and Tribal engagement and social impacts d) Evaluate fire benefits to other components of forest ecosystems (e.g., vegetation, watershed, wildlife habitat, forest carbon, drought tolerance) e) Use SFZs as contemporary reference areas for ecological restoration f) Integrate Indigenous knowledge and Tribal research questions and methodologies	a) Fernandes and Botelho 2003; Hunter and Robles 2020 b) Kane et al. 2019; Chamberlain et al. 2023 c) Mason et al. 2012; Lake et al. 2017 d) Boisramé et al. 2017; Wright et al. 2023; Earles et al. 2014; Laflower et al. 2016; Hurteau et al. 2016, 2019; Knapp et al. 2021 e) Meyer 2015; Jeronimo et al. 2019; Kreider et al. 2023 f) Hankins and Ross 2008; Lake et al. 2017
Outreach & Communication	Collaboration to build fire acceptance	a) Field visits to SFZ demonstration areas b) Online information tools (e.g.; StoryMaps, science briefs) c) Co-development with Tribal and managers of key messages to stakeholders, public, and the media about the value of SFZs d) Integration of cultural burning and beneficial fire in fire training and education programs	a) Toman et al. 2004 b) Cope et al. 2018; www.ginacova.com/portfolio c) Toman et al. 2006; Mason et al. 2012 d) Long et al. 2021; Meyer et al. 2021; CA Task Force 2022

million ha or 74% of the total area of the three National Forests (USDA FS 2023). PODs boundaries have now been identified for most of the National Forests in the western US (Supplemental Fig. 1).

During each National Forest's planning period, landscapes conducive to strategic applied beneficial fire use could be identified as discrete administrative zones that meet the following criteria: forests that 1) primarily had historically frequent-fire regimes (≤35 year mean fire return interval), 2) are remote (i.e., ≥1–2.4 km) from human habitation and infrastructure (Carlson et al. 2022), and 3) following PODS boundaries, have natural barriers (i.e., rock, water, or sparsely treed forests), roads, and/or managed fuel-reduced boundaries that can reliably constrain fire growth and high-intensity fire behavior. Within these SFZs, lightning ignitions are then evaluated using fire management decision support tools (i.e., the Wildland Fire Decision Support System) to determine if fuel and weather conditions are favorable for reducing fuels and achieving ecosystem restoration (Fillmore et al. 2021). If no suitable lightning ignition occurs within the desired fire return interval of the dominant forest types, prescribed or cultural fire can be initiated to complete the burn cycle. SFZs would be dynamic, shifting in response to changes in forest conditions adjacent to the SFZ boundary that augment or compromise the desired reduced fuel loads helping to contain fires.

SFZs potential application in the western US

To determine the potential extent and distribution of SFZs in the western US, we conducted a geospatial analysis focused on the eleven western States (Washington, Oregon, California, Idaho, Montana, Nevada, Utah, Arizona, New Mexico, Colorado, and

Table 2 Area (ha) of federally-managed, frequent-fire (FF) forests in 11 western US States that would qualify as potential SFZs using two WUI definitions, two minimum patch sizes (2,000 and 5000 ha) and two buffer sizes (1 and 2.4 km). States are listed in descending order by their area of potential SFZs using the individual building footprint WUI with a 2.4 km buffer and large patch size (≥ 5,000 ha) combination that is most restrictive for SFZ delineation

		Area (ha)					
		Individual building footprints + 2,400 m buffer		Building density threshold + 2,400 m buffer		Individual building footprints + 1,000 m buffer	
State (Area, million ha)	Fed. Freq. Fire (FF) Forest ha	5,000 ha (% of Fed FF)	2,000 ha (% of Fed FF)	5,000 ha (% of Fed FF)	2,000 ha (% of Fed FF)	5,000 ha (% of Fed FF)	2,000 ha (% of Fed FF)
California (40.9)	5,995,765	2,848,552 (47.5%)	3,014,578 (50.3%)	2,866,189 (47.8%)	3,041,667 (50.7%)	4,089,294 (68.2%)	4,234,909 (70.6%)
Oregon (25.1)	3,594,901	2,127,050 (59.2%)	2,192,176 (61.0%)	2,180,564 (60.7%)	2,244,825 (62.4%)	2,526,34 (70.3%)	2,621,430 (72.9%)
New Mexico (31.5)	2,314,856	930,525 (40.2%)	1,009,709 (43.6%)	1,160,583 (50.1%)	1,234,892 (53.3%)	1,416,762 (61.2%)	1,475,756 (63.8%)
Arizona (29.5)	1,754,701	825,817 (47.1%)	881,327 (50.2%)	835,138 (47.6%)	879,105 (50.1%)	1,123,940 (64.1%)	1,168,429 (66.6%)
Utah (22.0)	1,404,979	596,036 (42.4%)	690,688 (49.2%)	519,231 (37.0%)	623,081 (44.3%)	783,498 (55.8%)	861,535 (61.3%)
Idaho (21.6)	1,986,480	378,679 (19.1%)	533,966 (26.9%)	367,763 (18.5%)	513,751 (25.9%)	603,959 (30.4%)	773,841 (39.0%)
Washington (17.4)	725,385	265,758 (36.6%)	285,411 (39.3%)	275,545 (38.0%)	299,302 (41.3%)	388,708 (53.6%)	409,998 (56.5%)
Colorado (27.0)	2,075,561	180,988 (8.7%)	258,831 (12.5%)	216,863 (10.4%)	328,421 (15.8%)	435,993 (21.0%)	582,191 (28.0%)
Montana (38.1)	1,866,960	103,335 (5.5%)	203,474 (10.9%)	106,753 (5.7%)	205,504 (11.0%)	291,507 (15.6%)	480,095 (25.7%)
Wyoming (25.3)	341,943	38,655 (11.3%)	41,104 (12.0%)	44,775 (13.1%)	63,771 (18.6%)	60,070 (17.6%)	89,106 (26.1%)
Nevada (28.7)	382,567	12,943 (3.4%)	23,277 (6.1%)	17,867 (4.7%)	34,143 (8.9%)	21,902 (5.7%)	42,148 (11.0%)
Total	22,444,099	8,308,338 (37.0%)	9,134,540 (40.7%)	8,591,271 (38.3%)	9,468,461 (42.2%)	11,741,975 (52.3%)	12,739,439 (56.8%)
Number of patches (mean size)		278 (30,054)	547 (16,794)	274 (31,626)	562 (16,997)	291 (40,897)	625 (20,664)
% Wilderness		13%	13%	14%	15%	12%	13%

Wyoming). Using LANDFIRE data (LANDFIRE 2020), we first screened our analysis for forests that historically had frequent-fire regimes (≤ 35 years) and were managed by a federal agency (total area = 22.4 million ha) (Table 2). We then calculated two measures of the WUI. In the first measure, the most cautious, we identified WUI based on 125 million individual building locations, including remote single structures, using a readily available Microsoft data set (https:github.com/Microsoft/USBuildingFootprints). The second measure also uses the 125 million building locations but consolidates that information into a measure of housing density, which improved on the previous less precise US census housing data (Carlson et al. 2022). This improved approach defines WUI as areas where building density exceeds 6.17 units km^{-2} and includes Intermix WUI (where land cover is at least 50% wildland vegetation) and Interface WUI (where wildland vegetation represents < 50% of the area but is within 2.4 km of a wildland vegetation patch at least 5 km^2 in area that contains at least 75% vegetation). We then buffered the individual building locations and Carlson et al.'s (2022) building density-based WUI with a 2.4 km buffer, based on estimates by the California Fire Alliance of potential fire ember casting distance (Stewart et al. 2007).

Beyond these buffered WUI areas, we screened for federally owned frequent-fire forests in contiguous patches of ≥ 2,000 and ≥ 5,000 ha. We selected these two patch sizes because both sizes exceed the estimated mean size of historical wildfires (500–700 ha, Safford and Stevens 2017), are large enough to administer as a distinct zone (≥ 2,000 ha), or are ≥ the median size of western US PODs intersecting Wilderness or Roadless areas (≥ 5,000 ha [Supplemental Fig. 1]).

Ember spotting distance is highly variable and depends on many factors including weather, fuels, and ember size and shape (Koo et al. 2012). Under certain conditions ember transport distances can be large, but most loft over much smaller distances than 2.4 km (Albini 1983; Koo et al. 2010). To examine how buffer distance affected our estimate of SFZ number and size, we decreased the buffer between SFZs and individual structures to 1 km. We did not apply this buffer reduction to the WUI measure based on housing density because its calculation for interface WUI already includes a 2.4 km buffer and is focused on efficient allocation of fire suppression resources to reduce structure loss in the event of a wildfire. SFZs are areas where fires are intentionally set or not fully suppressed. Thus, it was essential that SFZs were separated from individual structures, a condition that the housing density-based estimate does not meet.

We provide estimates of potential SFZs in each of the eleven western States using WUI defined by each individual structure with either a 1 or 2.4 km buffer and combined with the two minimum patch sizes (Table 2). For comparison, we provide estimates of SFZs using the standard WUI metric based on housing density (Carlson et al. 2022) with a 2.4 km buffer. We also calculated the amount of each SFZ that is in Wilderness. We did so for two reasons. Although many existing areas designated for ecologically beneficial fire are in National Park or National Forest Wilderness, these areas often occur in higher elevations where forests did not historically experience frequent fires. We were also interested in knowing the percentage of Wilderness in potential SFZs because prescribed fire use in Wilderness is opposed by some stakeholders that view it as violating the Wilderness Acts edict of being "untrammeled by man."

Results

Across the 11 western States, the total area of potential SFZs ranges from 8.3 to 12.7 million ha (Table 2). These zones could contribute substantially to creating large areas where beneficial fire could be restored, thereby reducing future wildfire size and severity. The range in total area depended on how WUI was delineated, the chosen buffer width, and the minimum patch size. We considered WUI delineation by individual building footprint with a 2.4 km buffer as the most conservative calculation since it would remove area from potential SFZ designation even when only a single structure, of any type, was present. WUI delineation based on a structure density threshold of 6.17 units km^{-2} within both Intermix and Interface classified areas is more consistent with conceptual WUI definitions based upon aggregate housing densities (Radeloff et al. 2005; Stewart et al. 2007). Surprisingly, there was little difference in potential SFZ total area identified between the two WUI identification methods with 2.4 km buffers. On average, potential SFZ area decreased by only 3.4% when switching from using the housing density to the individual building footprint basis, suggesting substantial SFZ areas could be designated without imperiling remote, individual structures (Table 2). When buffer distance around each individual structure was reduced from 2.4 to 1.0 km, potential SFZ area increased by 40.4%, averaged between the two minimum patch sizes (Table 2). On average, decreasing minimum patch size from 5,000 to 2,000 ha increased SFZ total area by 9.5% and increased the number of patches by 206%. The SFZ area that fell within wilderness designation was only 12–15% (Table 2).

Potential SFZ locations are widely distributed across the western US (Fig. 1). States with a large area of SFZ areas include California, Oregon, New Mexico, Arizona, Utah, Idaho, and Washington (Table 2). With the exception of Idaho, the other six states in this group could treat fuels and restore 37–73% of their federally-managed, frequent-fire forests using SFZs. Idaho, Montana, and Colorado have sizable area of federally-managed, frequent-fire forests (2.0, 1.9, and 2.1 million ha, respectively), but less SFZ potential due to many remote structures and smaller contiguous patches of federal ownership. If the buffer of individual structures is reduced to 1 km and minimum patch size to 2,000 ha, the area and number of SFZ patches substantially increase in these three states (Table 2, Fig. 1). Wyoming and Nevada have limited area (< 400,000 ha) of federally owned frequent-fire forests and far fewer potential SFZs.

Applying potential operational delineations

All potential SFZs would need to be evaluated individually and in most cases their boundaries aligned with locally designed PODs delineations. As an example, we examined the SFZ and POD distribution in an area northeast of Fresno, CA, familiar to several of the coauthors, that is dominated by ponderosa pine and mixed-conifer forests (Fig. 2). Our analysis correctly identified the slopes of Patterson Mountain (center) as a potential SFZ. This remote area was repeatedly prescribed burned in the 1990s with minimal fire crews and at costs averaging $173 USD/ha (McCandliss 2002). The buffer decrease from 2.4 to 1.0 km is reflected by the purple 'rind' shrinking the circular gaps created by building structures (center), while adding to the (green) SFZ area. Increases in SFZ area also occur where a decrease to a 2,000 ha minimum patch size adds onto the central SFZ core area. Local knowledge and visualizing how buffer and patch size affect SFZ area aid in identifying which POD boundaries are best used.

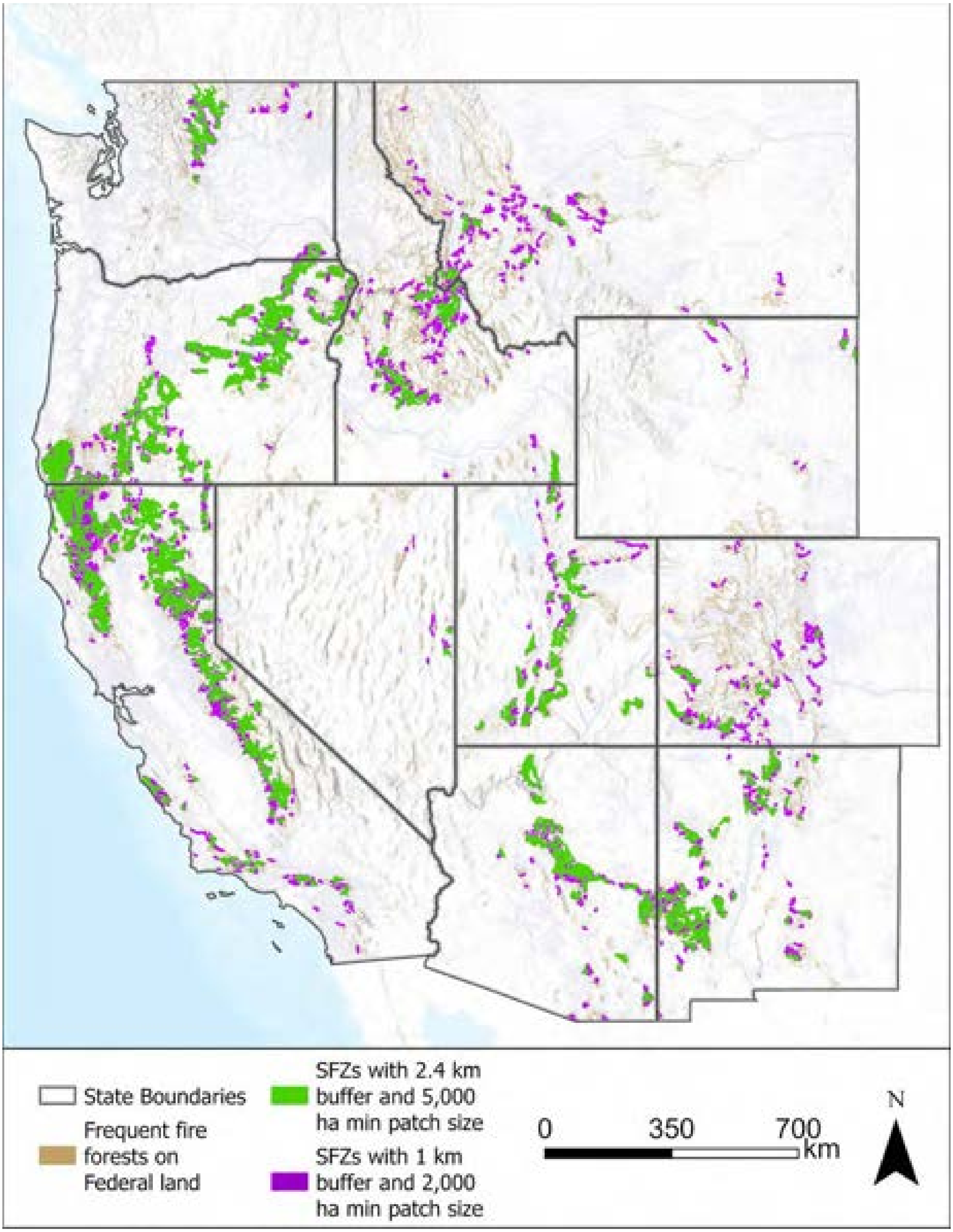

Fig. 1 Eleven western US states analyzed for potential SFZs. Tan shading indicates federally-managed, frequent-fire forests (≤ 35 years fire return interval). Green shading indicates potential SFZ patch locations of ≥ 5000 ha using a WUI based on a 2.4 km buffering of each individual building location. Purple shading indicates additional potential SFZ areas when the WUI buffer is reduced to 1.0 km and patch size is reduced to ≥ 2000 ha

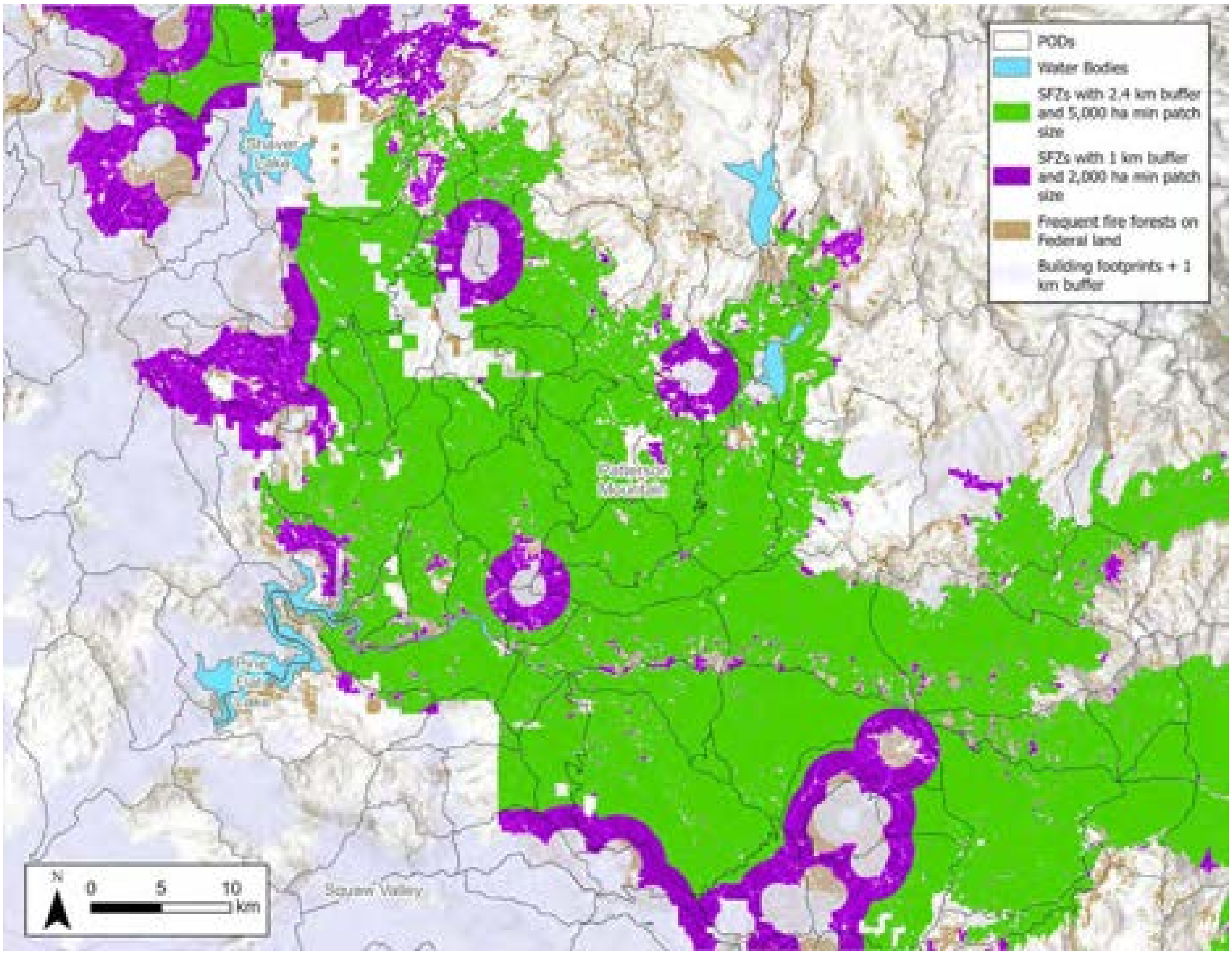

Fig. 2 Detailed image of a portion of the southern Sierra Nevada northeast of Fresno, CA, showing PODs, federally managed, frequent-fire forests, and potential SFZs. In the middle portion of the figure, forests cover most of the Sierra foothills between 1200–2400 m, while the upper 1/3 of the Fig. (2400–4400 m) displays high elevation red fir and lodgepole pine forest types where fire occurs relatively infrequently (e.g., every 50–200 years). Potential SFZ areas could be delineated by aggregating PODs that are dominated by the SFZ's shading

Managers can reinforce existing POD boundaries and build alternative control lines using pyrosilviculture principles (North et al. 2021). Often SFZs will reside in remote areas with limited access or wilderness constraints on applying mechanical treatments. Pyrosilviculture is designed to apply mechanical treatments to stands as appropriate, to facilitate the return of beneficial fire where fire-alone treatments will have uncertain outcomes (York et al. 2021a, b). It is also designed to apply prescribed and cultural burning, and wildfire managed for resource benefit to backcountry landscapes. Together, a portfolio of varied pyrosilviculture treatments can connect fuel reduction and restoration efforts across large landscapes (North et al. 2021), and increase the likelihood of more benign wildfire dynamics and outcomes.

Wildfires near SFZs may also provide opportunities for expanding or fortifying their boundaries. Recent papers (Meyer et al. 2021; Stevens et al. 2021; Larson et al. 2022; Long et al. 2023) have advanced ecological principles and frameworks for post-wildfire management designed to guide restoration efforts, including the expansion of beneficial fire use. These frameworks incorporate the fuels reduction 'work' of wildfires into postburn management plans for large landscapes and can help reinforce or buffer SFZ boundaries.

Research and monitoring

A primary challenge with burning SFZs is the fuel loading that has accumulated during the last century or more of fire suppression and exclusion. Setting moderate rather than aggressive weather and fuel moisture objectives for the initial fires can help, but as fires burn, conditions can change and managers often have to decide when to delay a burn, reduce or increase fire intensity, or constrain fire growth.

Natural range of variation (NRV) studies for different forest types can be used to evaluate spatial patterns of fine- to meso-scale (< 5–20 ha) heterogeneity in forest fuel and successional conditions (Veblen 2003; Safford and Stevens 2017; Meyers and North 2019). Small to medium-sized patches of previously burned areas serve for a time as 'fences' to subsequent fire spread (Moritz et al. 2011; Prichard et al. 2017; Povak et al. 2023), whereas forest areas that have not recently burned or whose surface fuels are grasses and shrubs act as 'corridors' of fire spread. These meadow and shrub areas tend to enable rapid but benign fire spread, which can provide managed wildfire conditions for low-intensity burns. Over time, these features reinforce a shifting mosaic of forest structures, tree densities, tree ages, and compositional differences, and a regime of frequent, predominantly low- to moderate-severity fire (North et al. 2009; Moritz et al. 2011; Perry et al. 2011; Povak et al. 2023). Drier south slopes and ridgetops are especially good places for decreasing tree density and creating clumped and gapped tree distributions (Lydersen and North 2012; Lydersen et al 2013; Fry et al. 2014). Larger (> 20–100 ha) patches of high-severity fire are occasionally important to restoring areas of critical nonforest conditions (see the reviews by Hessburg et al. 2016, 2019). However, frequent occurrence of very large high-severity patches (> 100 ha) can result in a loss of the ecosystem's fine-scale grain (Cova et al. 2023), suggesting a reduction in fire intensity is needed.

After a prescribed, cultural, or managed wildfire for resource benefit, the prevalence and scale of these patterns can be directly monitored with field plots (Ferandes and Botelho 2003; Hunter and Robes 2020), unmanned aerial vehicle (UAV) photography, or remotely sensed with tools such as LiDAR that can assess heterogeneity at multiple scales (Kane et al. 2019; Chamberlain et al. 2023). Tribes are best consulted to identify important cultural species (e.g., black oak [*Quercus kelloggii*]) to monitor how burns affect their abundance, distribution, and vitality (Hankins and Ross 2008; Long et al. 2021). Permanent plots, before/after hydrology modeling, and aerial or UAV photo interpretation established before and after the burn can assess fire effects on other ecosystem services such as water quantity and quality, carbon storage, and vegetation diversity (Boisrame et al. 2017; Hurteau et al. 2016; Wayman and North 2007). After several burns, an SFZ may serve as a contemporary reference area against which ecosystem restoration can be assessed (Meyer 2015; Jeronimo et al. 2019; Kreider et al. 2023). Both successes and failures will be instructive and should be documented.

Outreach and communication

SFZs will need public support that comes from understanding their role in reducing the risk of extreme wildfire. Agency sponsored field trips to local SFZs and recently managed wildfires or cultural burns can build that support particularly if discussions are treated as open dialogue. Online tools such as science briefs and Story Maps (e.g., Map | The Wise Path Forward [adaptiveforeststewardship.org]) can provide vetted information to counter the partial truths and illusion of legitimacy often found in Internet or published misinformation (Jones et al. 2022).

In Western culture there are few narratives about successfully living with fire. SFZs will likely be opposed by groups that feel threatened by fire, are intolerant of smoke, or believe that low- or moderate-severity fire destroys rather than renews wildlife habitat and forest ecosystems. Land management agency outreach can start by building the context for how people are part of the landscapes in which they live, a landscape where fire is inevitable (Donovan and Brown 2007). In contrast, Indigenous Communities have a long narrative history to share of living and working with fire (i.e., see Braiding-SweetgrassReport.pdf (washington.edu).

Before the arrival of Europeans, studies suggest fire burned extensive areas in the continental US (Leenhouts 1998). For example, it is estimated that up to 1.8 million ha burned each year in California alone (Stephens et al. 2007). There is ongoing debate about how much of this historical fire was anthropogenic but there is increasing evidence that cultural burning buffered Indigenous Communities from climate-driven increases in fire size and severity (Swetnam et al. 2016; Taylor et al. 2016; Roos et al. 2021, 2022). Although cultural burning may have been targeted at producing desired resources, these studies suggest it was also effective at interrupting fire spread and reducing fire severity over large areas. To live in a landscape that frequently burns, intentional fire is essential. This model of cultural burning reducing large-scale fire transmission is a useful lesson for why SFZs are needed in contemporary forests with high fuel loadings that facilitate fire contagion. This historical narrative of living with fire could also be bolstered with training programs in the combined use of cultural and prescribed burning practices (Lake et al. 2017; Long et al. 2021; Goode et al. 2022).

Impediments and opportunities

There are a number of entrenched impediments to wider use of ecologically beneficial fire (Miller et al. 2020) that will also be obstacles for SFZs. The recent Wildland Fire Commission report (WFMMC 2023) has a list of 148 Recommendations for addressing current impediments.

Here we discuss two, smoke and work force, that were highlighted by the Commission and may also provide opportunities for effecting change.

Fire suppression and the curtailment of cultural burning have created an unattainable expectation for smokeless skies, which were not accounted for when the Clean Air Act was established. Decades of fire exclusion have accumulated a substantial fuel surplus or "smoke debt" that will eventually be released (CARB 2021). SFZs allow greater control over the timing and amount of combustion and smoke released, by emphasizing fuel burning under moderate weather and fuel moisture conditions. Under these conditions fire produces much less harmful particulate matter (PM 2.5) per mass of fuel burned (Prichard et al. 2020), reducing smoke impacts on vulnerable human populations (Long et al. 2018; Schweitzer et al. 2019; D'Evelyn et al. 2022).

Recently, the US Environmental Protection Agency (EPA) tightened the National Ambient Air Quality Standard (NAAQS) for fine particulate matter ($PM_{2.5}$) from 12 to 9 µg m-3. Many of the counties that will fall out of attainment with this standard are in forest-fire prone regions of the western US (Supplemental Table 1). The largest concentration of these counties is in California, particularly in the Central Valley and Sierra Nevada. This area has experienced several extreme wildfires (e.g., 2015 Rough Fire, 2020 Creek Fire, 2020 SQF complex) but has extensive SFZ potential (Fig. 2). In an earlier 2016 regulation, known as the Exceptional Events Rule (Supplemental Table 1), the EPA provided a clear pathway to exclude emissions from 'exceptional events', which include prescribed burning and 'uncontrolled' wildfire, in determining regulatory compliance. However, treatment of emissions from wildfires managed for other than full suppression is not explicitly addressed in the Exceptional Events Rule. To provide necessary clarity, the EPA might consider expanding its Exceptional Events Rule to include all SFZ fires.

Another challenge with SFZs is the available workforce. Although the federal agencies have been hiring more firefighters, workforce capacity is still highly limited. Fire crews are often scarce when intentional fire would be most ecologically beneficial because this period, early to mid-fall, is also peak wildfire season in some regions of the country. Identifying and incorporating SFZs into National Forest plans and planning forest-wide prescribed fire projects, however, could motivate managers and appropriators to fund the hiring of needed crews that are dedicated to applying and working with ecologically beneficial fire within defined locales. Continued reliance on suppression firefighters to provide the needed work force during optimal burn conditions will continue to fall far short of the needs. A dedicated workforce is needed to develop high-end, proactive skill in working with controllable managed fire, prescribed fire, and cultural burning (Anderson 2005).

An increase in intentional prescribed and cultural burning could lead to year-round, place-based employment, providing fire personnel with continuous work and a home base. This will not appeal to all firefighters, but it would diversify work options for those seeking steady work without having to constantly travel to and stay at distant wildfires. This might be a means of increasing the hiring of Tribal fire practitioners and a catalyst for allowing Tribes to work across jurisdictional boundaries. As there is more collaboration with Tribes, fire personnel would gain better appreciation of what local areas and resources are important to Tribes and how ecologically beneficial fire can be best applied and managed to meet cultural objectives.

Conclusion

Wildfire and drought are dramatically changing western US landscapes, making a reactive, suppression-focused, fire-by-fire approach insufficient for altering emerging wildfire regimes under rapidly changing climate conditions. Wildfire and climate change are currently, and will continue to be, the largest, most substantial change agents in western US forests, and climate change will continue to increase burned area over the coming century (Abatzoglou et al. 2021). Adequately scaled increases in forest restoration can multiply the amount of beneficial fire on the landscape while simultaneously reducing the risk of large and destructive megafires. SFZs would serve as fire "sinks", reducing landscape fuel connectivity and potential burn transmission into the WUI. In forested landscapes, maintaining a large fuels-reduced area (i.e., 25–50%, Hessburg et al. 2019; Povak et al. 2023) would reduce the extent and negative impacts of many contemporary wildfires. SFZs are the most direct, efficient, and rapidly scalable path to meeting these target areas ahead of the next wildfire.

While there are inherent risks to working with rather than against fire, there is no risk-free future. The single greatest risk is to continue living with the threats of wildfires that escape initial suppression and often lead to increasingly large and severe wildfires. Risks associated with prescribed burning are likely the smallest, but constrained burn windows will keep prescribed fire footprints very small in comparison to wildfires (Miller et al. 2020). Intentionally using beneficial fire in SFZs can provide an initially intermediate level of risk, but the level will steadily decline as more area is managed by fire in the backcountry. There is likely no lower risk alternative than this. The risks associated with the no-action alternative (continued aggressive fire suppression) need to be honestly and openly assessed, and communicated (Calkin et al. 2014; Prichard et al. 2021; Hessburg et al. 2021). These are the highest risks of all. SFZs would allow managers to proactively and effectively mitigate wildfire risk while restoring forest ecosystems and their resilience.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-024-00282-y.

Supplementary Material 1: Supplemental Figure 1. PODs in the western US; a) Map of POD distribution in the western US (see Supplemental Table 1 for link); b) a graph of POD size in relation to housing density; and c) a table of the mean and median size (ha) of all PODs, those in the western US, and those that intersect wilderness and roadless areas.

Supplementary Material 2: Supplemental Table 1. List of the data types, their sources, and links where data and government publications can be downloaded.

Acknowledgements
We thank L. Clarke with the Climate and Wildfire Institute for her helpful review and editing of this manuscript. We also appreciate the support of the USFS PSW and PNW Research Stations. We thank C. Thomas and B. Skaggs, California Fire Restoration Group, A. Swan, U.C. Berkeley, and T. Pusina, Inyo National Forest, for discussion of concepts in this paper. We thank S. Clark, an attorney with Shute, Mihaly, and Weinberger LLP, who reviewed and edited the section discussing the EPA regulations and Exceptional Events Rule. We are grateful for the work of P. Bowden of the US Forest Service (retired) for refining and advocating for 'wildfire restoration' and 'wildfire maintenance' zones for Region 5, and M. Thompson's (Vibrant Plant) work in developing and implementing Potential Operational Delineations or PODs.

Authors' contributions
MPN developed the idea of SFZs; MPN, PFH, and MDM outlined the organization and structure of the manuscript; MPN and AR developed the analysis approach, figures, and tables; AR conducted the analysis, all authors made substantial contributions in drafting the manuscript, providing extensive editorial input, and citations during manuscript preparation and revision. All authors read and approved the final manuscript.

Funding
No additional or outside funding was used in developing this manuscript.

Availability of data and materials
Links to datasets, maps, and government reports are listed in the Supplemental Table 1.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Author details
[1]USDA Forest Service, PSW Research Station, Davis, CA 95618, USA. [2]Department of Natural Resources and Environmental Science & Program in Ecology, Evolution, & Conservation Biology, University of Nevada, Reno, NV 89557, USA. [3]Department of Geography and Planning, California State University, Chico, CA 95929, USA. [4]USDA Forest Service, PNW Research Station, Forestry Sciences Laboratory, Wenatchee, WA 98801, USA. [5]Biology Department, University of New Mexico, Albuquerque, NM 87131, USA. [6]Department of Forest, Rangeland, and Fire Sciences, University of Idaho, Coeur d'Alene, ID 83814, USA. [7]USDA Forest Service, Region 5 Ecology Program, Southern Sierra Province, Bishop, CA 93514, USA. [8]Department of Forest and Rangeland Stewardship, Colorado Forest Restoration Institute, Colorado State University, Fort Collins, CO 80523, USA. [9]Department of Environmental Science, Policy & Management, University of California, Berkeley, CA 94720, USA.

Received: 20 November 2023 Accepted: 6 May 2024
Published online: 21 May 2024

References

Abatzoglou, J.T., C.S. Juang, A.P. Williams, C.A. Kolden, and A.L. Westerling. 2021. Increasing synchronous fire danger in forests of the Western United States. *Geophysical Research Letters*. 48: e2020GL091377.

Albini, F.A. 1983. *Potential spotting distance from wind-driven surface fire*. Ogden, UT: USDA Forest Service, Intermountain Forest and Range Experiment Station, Research Paper INT-309.

Anderson, K. 2005. *Tending the wild: Native American knowledge and the management of California's natural resources*. Univ. of California Press, Berkeley, CA. 557 pp.

Boisramé, G., S. Thompson, B. Collins, and S. Stephens. 2017. Managed wildfire effects on forest resilience and water in the Sierra Nevada. *Ecosystems* 20: 717–732.

CA Task Force. 2022. California Wildfire and Forest Resilience Task Force. 2022. California's strategic plan for expanding the use of beneficial fire. California Wildfire and Forest Resilience Task Force. 53 p.

Calkin, D.E., J.D. Cohen, M.A. Finney, and M.P. Thompson. 2014. How risk management can prevent future wildfire disasters in the wildland-urban interface. *Proceedings of the National Academy of Sciences* 111: 746–751.

CARB 2021. *California's historical fire activity before modern fire suppression*. Unpublished report available at https://ww2.arb.ca.gov/wildfire-emissions.

Carlson, A.R., D.P. Helmers, T.J. Hawbaker, M.H. Mockrin, and V.C. Radelopp. 2022. The wildland-urban interface in the United States based on 125 million building locations. *Ecological Applications* 32: e2597.

Chamberlain, C.P., G.R. Cova, C.A. Cansler, M.P. North, M.D. Meyer, S.M.A. Jeronimo, and V.R. Kane. 2023. Consistently heterogeneous structures observed at multiple spatial scales across fire-intact reference sites. *Forest Ecology and Management* 550: 121478.

Cope, M.P., E.A. Mikhailova, C.J. Post, M.A. Schlautman, and P. Carbajales-Dale. 2018. Developing and evaluating an ESRI story map as an educational tool. *Natural Sciences Education* 47: 1–9.

Coppoletta, M., W. Brendecke, R. Bauer, R. Tompkins, and F. Heide. 2022. *Post-fire restoration opportunities for conifer forest in the 2021 Dixie and Sugar Fires. Pacific Southwest Region Ecology Program, USDA Forest Service*. 48 pages. https://www.fs.usda.gov/detail/r5/plants-animals/?cid=FSEPRD1087476.

Cova, G., V.R. Kane, S. Prichard, M. North, and C.A. Cansler. 2023. The outsized role of California's largest wildfires in changing forest burn patterns and coarsening ecosystem scale. *Forest Ecology and Management* 528: 120620.

D'Evelyn, S.M., J. Jung, E. Alvarado, J. Baumgartner, P. Caligiuri, R.K. Hagmann, S.B. Henderson, P.F. Hessburg, S. Hopkins, E.J. Kasner, and M.A. Krawchuk. 2022. Wildfire, smoke exposure, human health, and environmental justice need to be integrated into forest restoration and management. *Current Environmental Health Report* 9: 366–385.

Donovan, G.H., and T.C. Brown. 2007. Be careful what you wish for: The legacy of Smokey Bear. *Frontiers in Ecology and the Environment* 5: 73–79.

Earles, M., M. North, M. Hurteau, and M. 2014. Wildfire and drought dynamics destabilize carbon stores of fire-suppressed forests. *Ecological Applications* 24: 732–740.

Fernandes, P.M., and H.S. Botelho. 2003. A review of prescribed burning effectiveness in fire hazard reduction. *International Journal of Wildland Fire* 12: 117–128.

Fillmore, S.D., S.M. McCaffrey, and A.M. Smith. 2021. A mixed methods literature review and framework for decision factors that may influence the utilization of managed wildfire on federal lands, USA. *Fire* 4: 62.

Fry, D.L., S.L. Stephens, B.M. Collins, M.P. North, E. Franco-Vizcaino, and S.J. Gill. 2014. Contrasting spatial patterns in active-fire and fire-suppressed

Mediterranean climate old-growth, mixed conifer forests. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0088985.

Goode, R.W., S.F. Beard, and C. Oraftik. 2022. Putting fire on the land: The Indigenous people spoke the language of ecology, and understood the connectedness and relationship between land, water, and fire. *Journal of California and Great Basin Anthropology* 42: 85–95.

Hankins, D.L., and J. Ross. 2008. *Research on native terms: navigation and participation issues for native scholars in community research*, 263–282. Routledge: In: Partnerships for Empowerment.

Hessburg, P.F., T.A. Spies, D.A. Perry, C.N. Skinner, A.H. Taylor, P.M. Brown, S.L. Stephens, A.J. Larson, D.J. Churchill, N.A. Povak, P.H. Singleton, B. McComb, W.J. Zielinski, B.M. Collins, R.B. Salter, J.J. Keane, J.F. Franklin, and G. Riegel. 2016. Tamm Review: Management of mixed-severity fire regime forests in Oregon, Washington, and Northern California. *Forest Ecology and Management* 366: 221–250.

Hessburg, P.F., C.L. Miller, N.A. Povak, A.H. Taylor, P.E. Higuera, S.J. Prichard, M.P. North, B.M. Collins, M.D. Hurteau, A.J. Larson, C.D. Allen, S.L. Stephens, H.R. Huerta, C. Stevens-Rumann, L.D. Daniels, Z. Gedalof, R.W. Gray, V.R. Kane, D.J. Churchill, R.K. Hagmann, T.A. Spies, S.A. Parks, C.A. Cansler, R.T. Belote, T.T. Veblen, M.A. Battaglia, C. Hoffman, C.N. Skinner, and H.D. Safford. 2019. Climate, environment, and disturbance history govern resilience of western North American forests. *Frontiers in Ecology and Evolution* 7: 239.

Hessburg, P.F., S.J. Prichard, R.K. Hagmann, N.A. Povak, and F.K. Lake. 2021. Wildfire and climate change adaptation of western North American forests: A case for intentional management. *Ecological Applications* 31: e02432.

Hunter, M.E., and M.D. Robles. 2020. Tamm review: The effects of prescribed fire on wildfire regimes and impacts: A framework for comparison. *Forest Ecology and Management* 475: 118435.

Hurteau, M.D., S. Liang, K.L. Martin, M.P. North, G.W. Koch, and B.A. Hungate. 2016. Restoring forest structure and process stabilizes forest carbon in wildfire-prone southwestern ponderosa pine forests. *Ecological Applications* 26: 382–391.

Hurteau, M.D., M.P. North, G.W. Koch, and B.A. Hungate. 2019. Managing for disturbance stabilizes forest carbon. *Proceedings of the National Academy of Sciences* 116: 10193–10195.

Jaffe, M.R., M.R. Kreider, D.L. Affleck, P.E. Higuera, C.A. Seielstad, S.A. Parks, and A.J. Larson. 2023. Mesic mixed-conifer forests are resilient to both historical high-severity fire and contemporary reburns in the US Northern Rocky Mountains. *Forest Ecology and Management* 545: 121283.

Jeronimo, S.M.A., V.R. Kane, D.J. Churchill, J.A. Lutz, M.P. North, G.P. Asner, and J.F. Franklin. 2019. Forest structure and pattern vary by climate and landform across active-fire landscapes in the montane Sierra Nevada. *Forest Ecology and Management* 437: 70–86.

Jones, G.M., E.K. Vraga, P.F. Hessburg, M.D. Hurteau, C.D. Allen, R.E. Keane, T.A. Spies, M.P. North, B.M. Collins, M.A. Finney, J.M. Lydersen, and A.L. Westerling. 2022. Counteracting wildfire misinformation. *Frontiers in Ecology and the Environment* 20: 392–393.

Kane, V.R., B.N. Bartl-Geller, M.P. North, J.T. Kane, J.M. Lydersen, S.A. Jeronimo, B.M. Collins, and L.M. Moskal. 2019. First-entry wildfires can create opening and tree clump patterns characteristic of resilient forests. *Forest Ecology and Management* 454: e117659.

Kimmerer, R.W., and F.K. Lake. 2001. The role of indigenous burning in land management. *Journal of Forestry* 99: 36–41.

Knapp, E.E., A.A. Bernal, J.M. Kane, C.J. Fettig, and M.P. North. 2021. Variable thinning and prescribed fire influence tree mortality and growth during and after a severe drought. *Forest Ecology and Management* 479: 118595.

Koo, E., P.J. Pagni, D.R. Weise, and J.P. Woycheese. 2010. Firebrands and spotting ignition in large-scale fires. *International Journal of Wildland Fire* 19: 818–843.

Koo, E., R.R. Linn, P.J. Pagni, and C.B. Edminster. 2012. Modelling firebrand transport in wildfires using HIGRAD/FIRETEC. *International Journal of Wildland Fire* 21: 396–417.

Kreider, M.R., M.R. Jaffe, J.K. Berkey, S.A. Parks, and A.J. Larson. 2023. The scientific value of fire in wilderness. *Fire Ecology* 19: 36.

Laflower, D.M., M.D. Hurteau, G.W. Koch, M.P. North, and B.A. Hungate. 2016. Climate-driven changes in forest succession and the influence of management on forest carbon dynamics in the Puget Lowlands of Washington State, USA. *Forest Ecology and Management* 362: 194–204.

Lake, F.K., V. Wright, P. Morgan, M. McFadzen, D. McWethy, and C. Stevens-Rumann. 2017. Returning fire to the land: Celebrating traditional knowledge and fire. *Journal of Forestry* 115: 343–353.

LANDFIRE. 2020. *Fire Regime Group Layer, LANDFIRE 2.0.0, US Department of the Interior, Geological Survey, and US Department of Agriculture*. Accessed 1 November 2023 at http://www.landfire/viewer.

Larson, A.J., S.M. Jeronimo, P.F. Hessburg, J.A. Lutz, N.A. Povak, C.A. Cansler, V.R. Kane, and D.J. Churchill. 2022. Tamm Review: Ecological principles to guide post-fire forest landscape management in the Inland Pacific and Northern Rocky Mountain regions. *Forest Ecology and Management* 504: 119680.

Leenhouts, B. 1998. Assessment of biomass burning in the conterminous United States. Conservation Ecology [online] 2(1): 1. Available from the Internet. URL: http://www.consecol.org/vol2/iss1/art1/.

Long, J.W., L.W. Tarnay, and M.P. North. 2018. Aligning smoke management with ecological and public health goals. *Journal of Forestry* 116: 76–86.

Long, J.W., F.K. Lake, and R.W. Goode. 2021. The importance of Indigenous cultural burning in forested regions of the Pacific West, USA. *Forest Ecology and Management* 500: 119597.

Long, J.W., D. Walsh, M. Coppoletta, R.E. Tompkins, M.D. Meyer, C. Isbell, G.N. Bohlman, and M.P. North. 2023. *Interventions to restore wildfire-altered forest in California*. Gen.Tech. Rep. PSW-GTR-278. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 105p. https://doi.org/10.2737/PSW-GTR-278.

Lydersen, J., and M. North. 2012. Topographic variation in active-fire forest structure under current climate conditions. *Ecosystems* 15: 1134–1146.

Lydersen, J.M., M.P. North, E.E. Knapp, and B.M. Collins. 2013. Quantifying spatial patterns of tree groups and gaps in mixed-conifer forests: Reference conditions and long-term changes following fire suppression and logging. *Forest Ecology and Management* 304: 370–382.

Marks-Block, T., F.K. Lake, B.R. Bliege Bird, and L.M. Curran. 2021a. Revitalized Karuk and Yurok cultural burning to enhance California hazelnut for basketweaving in northwestern California, USA. *Fire Ecology* 17: 1–20.

Marks-Block, T., and W. Tripp. 2021b. Facilitating prescribed fire in Northern California through Indigenous governance and interagency partnerships. *Fire* 4: 37.

Mason, L., G. White, G. Morishima, E. Alvarado, L. Andrew, F. Clark, M. Durglo, J. Durglo, J. Eneas, J. Erickson, M. Friedlander, K. Hamel, C. Hardy, T. Harwood, F. Haven, E. Isaac, L. James, R. Kenning, A. Leighton, P. Pierre, C. Raish, B. Shaw, S. Smallsalmon, V. Stearns, H. Teasley, M. Weingart, and S. Wilder. 2012. Listening and learning from traditional knowledge and western science: A dialogue on contemporary challenges of forest health and wildfire. *Journal of Forestry* 110: 187–193.

McCandliss, D.S. 2002. Prescribed burning in the Kings River Ecosystem Project Area: lessons learned. Pages 37–45 in: Verner, J., ed. *Proceedings of a symposium on the Kings River sustainable forest ecosystems project: progress and current status. Gen. Tech. Rep. PSW-GTR- 183*. Albany, CA: US Department of Agriculture, Forest Service, Pacific Southwest Research Station.

Meyer, M.D. 2015. Forest fire severity patterns of resource objective wildfires in the southern Sierra Nevada. *Journal of Forestry* 113: 49–56.

Meyer, M.D., and M.P. North. 2019. *Natural range of variation of red fir and subalpine forests in the Sierra Nevada Bioregion. PSW-GTR-263*, 135. Albany, CA: USDA Forest Service, Pacific Southwest Research Station.

Meyer, M.D., J.W. Long, H.D. Safford, S.C. Sawyer, M.P. North, and A.M. White. 2021. Principles of postfire restoration. Pages 1–30 in Meyer, M.D.; Long,J.W.; Safford, H.D, eds. 2021. *Postfire restoration framework for National Forests in California*. Gen. Tech. Rep. PSW-GTR-270. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 204p.

Miller, R.K., C.B. Field, and K. 2020. *J. Mach. Barriers and Enablers for Prescribed Burns for Wildfire Management in California. Nature Sustainability* 3: 101–109.

Moritz, M.A., P.F. Hessburg, and N.A. Povak. 2011. Native fire regimes and landscape resilience. In *The Landscape Ecology of Fire. Ecological Studies, vol 213*, ed. D. McKenzie, C. Miller, and D. Falk. Springer: Dordrecht, Germany.

North, M., P. Stine, K. O'Hara, W. Zielinski, and S. Stephens. 2009. An ecosystem management strategy for Sierran mixed-conifer forests. USDA Forest Service, PSW General Technical Report. PSW-GTR-220.

North, M., A. Brough, J. Long, B. Collins, P. Bowden, D. Yasuda, J. Miller, and N. Suighara. 2015a. Constraints on mechanized treatment significantly limit mechanical fuels reduction extent in the Sierra Nevada. *Journal of Forestry* 113: 40–48.

North, M.P., S.L. Stephens, B.M. Collins, J.K. Agee, G. Aplet, J.F. Franklin, and P.Z. Fulé. 2015b. Reform forest fire management. *Science* 349: 1280–1281.

North, M.P., R.A. York, B.M. Collins, M.D. Hurteau, G.M. Jones, E.E. Knapp, L. Kobziar, H. McCann, M.D. Meyer, S.L. Stephens, R.E. Tompkins, and C.L. Tubbesing. 2021. Pyrosilviculture needed for landscape resilience of dry western U.S. forests. *Journal of Forestry* 119: 520–544.
North, M.P., R.E. Tompkins, A.A. Bernal, B.M. Collins, S.L. Stephens, and R.A. York. 2022. Operational resilience in western US frequent-fire forests. *Forest Ecology and Management* 507: 120004.
Parks, S.A., L.M. Holsinger, C. Miller, and C.R. Nelson. 2015. Wildland fire as a self-regulating mechanism: The role of previous burns and weather in limiting fire progression. *Ecological Applications* 25: 1478–1492.
Perry, D.A., P.F. Hessburg, C.N. Skinner, T.A. Spies, S.L. Stephens, A.H. Taylor, J.F. Franklin, B. McComb, and G. Riegel. 2011. The ecology of mixed severity fire regimes in Washington, Oregon, and Northern California. *Forest Ecology and Management* 262: 703–717.
Povak, N.A., P.F. Hessburg, R.B. Salter, S.J. Prichard, and R.W. Gray. 2023. System-level feedbacks of active fire regimes in large landscapes. *Fire Ecology* 19: 45.
Prichard, S.J., C.S. Stevens-Rumann, and P.F. Hessburg. 2017. Tamm Review: Shifting global fire regimes: Lessons from reburns and research needs. *Forest Ecology and Management* 396: 217–233.
Prichard, S., S. O'Neill, P. Eagle, A. Andreu, B. Drye, J. Dubowey, S. Urbanski, and T. Strand. 2020. Wildland fire emission factors in North America: Synthesis of existing data, measurement needs and management applications. *International Journal of Wildland Fire* 29: 132–147.
Prichard, S.J., P.F. Hessburg, R.K. Hagmann, N.A. Povak, S.Z. Dobrowski, M.D. Hurteau, V.R. Kane, R.E. Keane, L.N. Kobziar, C.A. Kolden, and M. North. 2021. Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications* 31: e02433.
Quinn-Davidson, L.N., and J.M. Varner. 2012. Impediments to prescribed fire across agency, landscape and manager: An example from northern California. *International Journal of Wildland Fire* 21: 210–218.
Radeloff, V.C., R.B. Hammer, S.I. Stewart, J.S. Fried, S.S. Holcomb, and J.F. McKeefry. 2005. The wildland-urban interface in the United States. *Ecological Applications* 15: 799–805.
Roos, C.I., T.W. Swetnam, T.J. Ferguson, M.J. Liebmann, R.A. Loehman, J.R. Welch, E.Q. Margolis, C.H. Guiterman, W.C. Hockaday, M.J. Aiuvalasit, and J. Battillo. 2021. Native American fire management at an ancient wildland–urban interface in the Southwest United States. *Proceedings of the National Academy of Sciences* 118: e2018733118.
Roos, C.I., C.H. Guiterman, E.Q. Margolis, T.W. Swetnam, N.C. Laluk, K.F. Thompson, C. Toya, C.A. Farris, P.Z. Fulé, J.M. Iniguez, and J.M. Kaib. 2022. Indigenous fire management and cross-scale fire-climate relationships in the Southwest United States from 1500 to 1900 CE. *Science Advances* 8: eabq3221.
Safford, H.D. and J.T. Stevens. 2017. *Natural range of variation for yellow pine and mixed-conifer forests in the Sierra Nevada, Southern Cascades, and Modoc and Inyo National Forests, California, USA*. Gen. Tech. Rep. PSW-GTR-256. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 229p.
Schultz, C.A., S.M. McCaffrey, and H.R. Huber-Stearns. 2019. Policy barriers and opportunities for prescribed fire application in the western United States. *International Journal of Wildland Fire* 28: 874–884.
Schweizer, D., H.K. Preisler, and R. Cisneros. 2019. Assessing relative differences in smoke exposure from prescribed, managed, and full suppression wildland fire. *Air Quality and Atmospheric Health* 12: 87–95.
Scott, J.H., M.P. Thompson, and D.E. Calkin. 2013. *A wildfire risk assessment framework for land and resource management. Gen. Tech. Rep. RMRS-GTR-315*. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 83 p. https://doi.org/10.2737/rmrs-gtr-315.
Stephens, S.L., R.E. Martin, and N.E. Clinton. 2007. Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. *Forest Ecology and Management* 251: 205–216.
Stevens, J.T., C.M. Haffey, J.D. Coop, P.J. Fornwalt, L. Yocom, C.D. Allen, A. Bradley, O.T. Burney, D. Carril, M.E. Chambers, and T.B. Chapman. 2021. Tamm Review: Postfire landscape management in frequent-fire conifer forests of the southwestern United States. *Forest Ecology and Management* 502: 119678.
Stewart, S.I., V.C. Radeloff, R.B. Hammer, and T.J. Hawbaker. 2007. Defining the wildland-urban interface. *Journal of Forestry* 105: 201–207.
Swetnam, T.W., J. Farella, C.I. Roos, M.J. Liebmann, D.A. Falk, and C.D. Allen. 2016. Multiscale perspectives of fire, climate and humans in western North America and the Jemez Mountains, USA. *Philosophical Transactions of the Royal Society b: Biological Sciences* 371: 20150168.
Taylor, A.H., V. Trouet, C.N. Skinner, and S. Stephens. 2016. Socioecological transitions trigger fire regime shifts and modulate fire–climate interactions in the Sierra Nevada, USA, 1600–2015 CE. *Proceedings of the National Academy of Sciences* 113: 13684–13689.
Thompson, M.P., P. Bowden, A. Brough, J.H. Scott, J. Gilbertson-Day, A. Taylor, J. Anderson, and J.R. Haas. 2016. Application of wildfire risk assessment results to wildfire response planning in the southern Sierra Nevada, California, USA. *Forests* 7: 64.
Thompson, M.P., C.D. O'Connor, B.M. Gannon, M.D. Caggiano, C.J. Dunn, C.A. Schultz, D.E. Calkin, B. Pietruszka, S.M. Greiner, R. Stratton, and J.T. Morisette. 2022a. Potential operational delineations: New horizons for proactive, risk-informed strategic land and fire management. *Fire Ecology* 18: 17. https://doi.org/10.1186/s42408-022-00139-2.
Thompson, M.P., K.C. Vogler, J.H. Scott, and C. Miller. 2022b. Comparing risk-based fuel treatment prioritization with alternative strategies for enhancing protection and resource management objectives. *Fire Ecology* 18: 1–20.
Toman, E., B. Shindler, and M. Brunson. 2006. Fire and fuel management communication strategies: Citizen evaluations of agency outreach activities. *Society and Natural Resources* 19: 321–336.
Toman, E., B. Shindler, M. Reed, and M. 2004. Prescribed fire: The influence of site visits on citizen attitudes. *The Journal of Environmental Education* 35: 13–33.
USDA. 2014. *A National Cohesive Wildland Fire Management Strategy. US Department of Agriculture, Forest Service; Department of the Interior, Office of Wildland Fire Coordination*. Washington, DC: Wildland Fire Leadership Council.
USDA. 2023. *Forest Service FEIS for Sierra and Sequoia forest plans*. Available online at https://www.fs.usda.gov/detail/r5/landmanagement/planning/?cid=STELPRD3802842.
Vaillant, N.M., and E.D. Reinhardt. 2017. An evaluation of the Forest Service hazardous fuels treatment program—Are we treating enough to promote resiliency or reduce hazard? *Journal of Forestry* 115: 300–308.
Van Wagtendonk, J.W. 2007. The history and evolution of wildland fire use. *Fire Ecology* 3: 3–17.
Veblen, T.T. 2003. Historic range of variability of mountain forest ecosystems: Concepts and applications. *The Forestry Chronicle* 79: 223–226.
Wayman, R., and M. North. 2007. Initial response of a mixed-conifer understory plant community to burning and thinning restoration treatments. *Forest Ecology and Management* 239: 32–44.
WFMMC. 2023. *On Fire: The Report of the Wildland Fire Mitigation and Management Commission*, 328. Washington, D.C.: US Government Publishing Office.
Williams, J.N., L. Quinn-Davidson, H.D. Safford, A. Grupenhoff, B.R. Middleton, J. Restaino, E. Smith, C. Adlam, and H. Rivera-Huerta. 2024. Overcoming obstacles to prescribed fire in the North American Mediterranean climate zone. *Frontiers in Ecology and the Environment* 22: e2687.
Wright, M.E., M.Z. Peery, J. Ayars, B.P. Dotters, K.N. Roberts, and G.M. Jones. 2023. Fuels reduction can directly improve spotted owl foraging habitat in the Sierra Nevada. *Forest Ecology and Management* 549: 121430.
York, R.A., J. Levine, K. Russell, and J. Restaino. 2021a. Opportunities for winter prescribed burning in mixed conifer plantations of the Sierra Nevada. *Fire Ecology* 17: 1–16.
York, R.A., H. Noble, L.N. Quinn-Davidson, and J.J. Battles. 2021b. Pyrosilviculture: Combining prescribed fire with gap-based silviculture in mixed-conifer forests of the Sierra Nevada. *Canadian Journal of Forest Research* 51: 781–791.
Young, J.D., A.M. Evans, J.M. Iniguez, A.E. Thode, M.D. Meyer, S.J. Hedwall, S. McCaffrey, S. Patrick, and C.H. Huang. 2020. Effects of policy change on wildland fire management strategies: Evidence for a paradigm shift in the western US? *International Journal of Wildland Fire* 29: 857–877.

Publisher's Note