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Perspectives: The pace and scale challenge: Leveraging wildfire footprints to increase forest resilience to future high-severity fire

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ABSTRACT

In historically frequent fire forests, wildfires are burning larger areas and driving forest loss across western North America, yet they also produce extensive low- to moderate-severity effects that can be leveraged to harden landscapes against future high-severity fire. Here, we operationalize prior conceptual calls by presenting a framework that identifies opportunities to leverage recent wildfire footprints via three management pathways to increasing resistance to high-severity fire: *create* (use burned edges as containment lines to treat adjacent unburned forest), *enhance* (apply mechanical treatment and prescribed fire or wildfire managed for resource objectives to areas with one prior beneficial disturbance), and *maintain* (sustain high-resistance stands with recurring fire). We quantify the extent of these opportunities across California's Sierra Nevada yellow pine-mixed conifer forests at the Potential Operational Delineations (PODs) scale and outline policy options to act within limited post-fire windows. This work can support increasing resistance to high-severity fire across the landscape, highlighting how leveraging wildfire has the potential to save time and money, lower operational risk under suitable conditions, and promote pyrodiversity and biodiversity.

1. Introduction

Uncharacteristically large and destructive wildfires have become increasingly common in western North American forests (Dennison et al., 2014, Keeley and Syphard 2021). In California, 19 of the 20 largest fires in the State's history, each exceeding 77,700 ha (190,000 acres), have occurred since 2003 (CAL FIRE 2024). In historically frequent-fire forests, the causes of these changes in fire extent, severity, and spatial pattern are generally attributed to more than a century of fire suppression and to climate change (Busenberg, 2004, Parks and Abatzoglou, 2020). Although these forests are adapted to fire, the size and severity of large contemporary wildfires far exceed historical precedents and are resulting in substantial forest loss (Arno, 2000, Hagmann et al., 2021, Steel et al., 2023). Across the western United States, the annual proportion burned at high severity increased 15-fold while the area burned increased 10-fold from 1985 to 2022 (Parks et al., 2025).

These wildfire trends demand not only an increase in the pace and scale of fuel treatments, but also new approaches to working with fire on the landscape. There are, however, many roadblocks to increasing the implementation of fuel treatments, including mechanical treatments and beneficial fire treatments: prescribed fire, cultural burning, and managing wildfire for resource objectives ("RO wildfire"). This is evident in the scale of fuel treatments in the yellow pine and mixed conifer forest of the Sierra Nevada, where from 2001 to 2022 the average annual treatment rate was only 5098 ha for prescribed fire (broadcast burns or pile burning) and 16,879 ha for mechanical treatments. Mechanical treatments include any silviculture treatment aimed at stand density management (Maguire et al., 2015) that is used to meet

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Table 1
Resistance pathways that leverage wildfire footprints and where they apply based on past disturbances, current and target resistance, and management actions to increase resistance to future high-severity fire.

	Create	*Enhance*		*Maintain*
Management goal	Begin building resistance in long-unburned forest	Increase resistance with additional treatment		Positive feedback loop to maintain resistance with beneficial fire
Landscape context	Untreated/ unburned forest adjacent to wildfire perimeter, unburned islands	Mechanically treated stand adjacent to wildfire perimeter; mechanically-treated islands	Within a wildfire footprint	Within a wildfire footprint
Disturbance history (10-yr)	None	1 mechanical treatment	1 beneficial fire	2 + beneficial disturbances (fire + fire, mechanical treatment + fire)
Resistance class (In year 10)	None	Low	Moderate	High
Target resistance class	Low to moderate	Moderate	High	Maintain high
Potential management actions	Mechanical treatment if needed Prescribed fire; cultural burns; RO wildfire	No mechanical treatment needed	Thin dead trees (or live if too many)	

fuel reduction, restoration, and/or timber harvest goals. Even combined, these treatments are a small fraction of the 2.3-million-hectare extent of this forest type (Shive et al., 2025).

There are numerous reasons why prescribed fire, cultural burning, and RO wildfire are particularly difficult to implement. Prescribed fire is restricted to relatively narrow "burn windows" which have mostly been limited to multiple days in spring and fall (Striplin et al., 2020), and recent work suggests that these windows are shifting because of climate change (Baijnath-Rodino et al., 2022, Swain et al., 2023). Prescribed fire also faces other obstacles, including environmental compliance, logistical support, liability considerations, agency culture, lack of incentives, risk aversion, lack of available fire-qualified personnel, and inability or unwillingness to use off-season burn windows (Kolden, 2019, Schultz et al., 2019, Miller et al., 2020, Striplin et al., 2020, Williams et al., 2024). RO wildfire faces many of the same barriers as prescribed fire, including overcoming risk aversion and limited availability of resources (Young et al., 2020, Miller et al., 2020). The challenges in implementing prescribed fire or RO wildfire are particularly alarming because these types of lower intensity fire-related disturbances are critical for reducing fire risk (Davis et al., 2024).

Meanwhile, low to moderate severity wildfire is reducing surface fuels and retaining mature trees (Das et al., 2025), essentially treating far more area than mechanical treatments and prescribed fire treatments (North et al., 2021, Shive et al., 2025). From 2012–2022, beneficial wildfire, defined as low to moderate severity fire regardless of how the wildfire was managed (e.g. ranging from full suppression to RO wildfire), impacted seven times the area of beneficial fire treatments in the Sierra Nevada's mixed-conifer forest (Shive et al., 2025). We recommend that forest managers consider working in and around recent wildfire footprints to increase the pace and scale of fuel treatments. They can do this by capitalizing on two key benefits of recent wildfires. First, the burned footprint can create a reduced fuel condition where adjacent burns can occur with potentially lower operational complexity (Thompson et al., 2016, North et al., 2021, Shive et al., 2025). Second, where the beneficial wildfire was a "first entry" since the suppression era began, follow-up treatments can increase resistance to future high-severity fire.

We build on prior conceptual calls to leverage recent wildfire footprints to increase the pace and scale of fuel treatments (North et al., 2021, Meyer et al., 2021, Larson et al., 2022, Jones and Tingley, 2022, Tortorelli et al., 2024, Shive et al., 2025) by operationalizing a framework that managers can apply now. Building off Shive et al. (2025), we define forest resistance to high-severity fire in relation to fuel conditions, which are in turn influenced by recent wildfires and management treatments. In this paper, we first describe three pathways (*create*, *enhance*, *maintain*) for leveraging wildfire footprints to increase resistance to high-severity fire across the landscape (Table 1). Next, we quantify the extent of the three pathways across the Sierra Nevada yellow pine-mixed conifer forests at the scale of Potential Operational Delineations (PODs), an existing land management unit defined by potential fire control features. PODs are used by the U.S. Forest Service and more recently by state fire agencies (e.g., CAL FIRE; SB1101 2024) to pre-plan wildfire response strategies and mechanical treatments prior to reintroducing fire (Thompson et al., 2022). Finally, we outline policy options to act within limited post-fire windows and consider how strategic modifications to the environmental compliance process could incentivize timely management of burned areas.

2. Pathways to resistance

2.1. *Create*

In long unburned forests, an initial beneficial disturbance is needed to begin the process of *creating* resistance to future high-severity fire (Table 1). To *create* resistance, managers typically use mechanical treatments, prescribed fire, or RO wildfire without consideration of leveraging recent wildfire footprints. Managers could strategically utilize burned edges (e.g. "the black") as containment lines for prescribed fire or resource benefit wildfire, with additional mechanical pre-fire treatments as needed. This potential is illustrated by studies that have documented how burned areas can either inhibit reburning or moderate subsequent fire severity. The positive effects typically last 6–12 years in warm and dry areas, with the duration dependent on the initial fire severity and local fuel conditions (Parks et al., 2015, Stevens-Rumann et al., 2016, Buma et al., 2020). In the Sierra Nevada, Cascade, and Klamath mountains, Tortorelli et al. (2024) found that the moderating effect of previous wildfire was most pronounced during the first six years after high-severity fire. Evidence on the strength of the moderating effect is equivocal under extreme conditions. Some studies have found that past fires moderate future fire severity even under extreme fire weather (Stevens-Rumann et al., 2016, Tortorelli et al., 2024), whereas others document reduced effectiveness in high-wind, plume-driven wildfires (Parks et al., 2015; Taylor et al., 2022). These divergent findings highlight that there will be substantial variation in a wildfire's ability to act as a fuel break, but wildfire-related surface fuel reduction (Das et al., 2025) will still likely offer more opportunities compared to unburned forests.

Fine fuels reaccumulate quickly on many sites over the first decade, particularly in high productivity sites, which can reduce the potential to use burned areas as control lines (Buma et al., 2020). As standing dead trees (snags) killed by fire fall over time, the buildup of coarse woody surface fuels that can sustain severe reburns is a risk that is particularly high in areas that burned at high severity (Lydersen et al., 2019, Jasperse et al., 2025). Such fuel-rich areas are susceptible to high intensity fire and can potentially end up expanding the initial high-severity patch size and result in more forest loss. Another concern with high-severity burns is hazardous snags that can be dangerous for fire personnel and require mitigation before using a burned edge as a containment line (Dunn et al., 2019). Both coarse woody surface fuels and snags could be reduced prior to utilizing burned edges, where there is risk. However, based on past studies (Parks et al., 2015, Stevens-Rumann et al., 2016, Buma et al., 2020, Tortorelli et al., 2024), we expect that in many cases burned edges could be suitable containment lines when the fire weather conditions are not extreme, with less preparation than when adjacent lands are long unburned.

Using these existing burned edges could reduce costs associated with digging fire lines or mechanical treatments along roads or ridges to reduce the risk of escape and to increase firefighter safety while implementing prescribed fire or RO wildfire. For prescribed fire, the benefits of reduced preparation costs are expected to be largest in the first 1–3 years postfire, when fuel loads are exceptionally low. Burned areas are already included in the Potential Control Location Suitability Model (O'Connor et al., 2017) along with water bodies, roads, and other places where fire has a medium-to-high probability of being contained, highlighting their potential for use as control lines. This data is updated annually and used for both pre-fire fuels reduction planning and during wildfire incident management (USDA 2025).

Additionally, patches of untreated/unburned vegetation surrounded by burned area (i.e., untreated/unburned islands within fire perimeters) provide naturally bounded burn units that can help reduce escape risk due to availability of existing hardened edges for containment. Treating unburned islands with mechanical treatments and fire or fire alone provides a way to scale up treatment sizes to bigger areas with a lower risk of escape and reduced cost of constructing control lines.

2.2. Enhance

While an initial first-entry treatment (active management treatment or beneficial wildfire) is an important start, very few stands reach target conditions with only one treatment (Stephens et al., 2009). An additional burn or mechanical treatment is frequently needed to *enhance* resistance. *Enhance* comprises two scenarios of past disturbance: first entry by wildfire that needs a second entry treatment, or first entry by mechanical treatment that needs follow up treatment with beneficial fire. If wildfire is a first-entry treatment, the stand could be thinned if the future fuel accumulation from the dead trees is a concern, or if postfire live tree densities still exceed desired conditions. These trees could be pile burned or sold to help offset restoration costs. Alternatively, a broadcast burn could also be used once enough surface fuels reaccumulate to carry the fire (~5–10 years). Certain places may not require mechanical treatment to *enhance* resistance and may only need prescribed fire or RO wildfire as a follow up treatment, which could save money on implementation costs.

In addition to areas with initial beneficial wildfire treatments, mechanically-treated areas adjacent to burned edges also offer opportunities to *enhance* resistance with a follow-up burn treatment. While likely less common, mechanically-treated areas that are surrounded by burned edges could be a lower risk and lower cost target for implementing prescribed fire or RO wildfire, than unburned/untreated islands.

Prioritizing re-burning in areas with low or moderate resistance could safeguard the time and money spent on environmental compliance (NEPA/CEQA) since the reduced fuel conditions means that these areas are unlikely to re-burn severely before the paperwork is finished. By contrast, planners working in long-unburned forests are up against the clock – these areas are at high risk of burning in a high-severity fire before the compliance and subsequent treatments are implemented, and any fuel reduction or ecological gains are realized. Focusing on burning in low to moderate severity areas will likely also create less smoke, potentially reduce the risk of escape, and may enable the use of a broader burn window for prescribed fire and RO wildfire. The "burn-the-burn" approach may also cause existing snags to fall and reduce snag hazards to fire responders (Dunn et al., 2019).

2.3. Maintain

After two or more beneficial disturbances, with at least one of those being beneficial wildfire or prescribed fire, stands can be much more resistant to high-severity fire (Davis et al., 2024) and may approach target conditions that are consistent with forests under an intact frequent fire regime (Stephens et al., 2009, 2012, Safford & Stevens 2017). However, even here, fuel re-accumulation through time means that an additional future disturbance is required to *maintain* resistance conditions. Ideally, the *maintain* pathway could be a positive feedback loop with beneficial fire on a somewhat less frequent time interval. Over time, by *enhancing* resistance across the landscape, managers could expand the number of PODs with high resistance to high-severity fire, shifting more of the landscape into a *maintain* pathway. For example, forest managers have managed RO wildfire for over 50 years in the Illilouette Creek Basin in Yosemite National Park, creating a complex mosaic of vegetation and fuels that subsequently limit the spread of individual fires (Collins et al., 2007). After five decades of consistent management, much of this area has transitioned into a self-regulating system that only requires continued periodic fire to be maintained as a pyrodiverse landscape.

2.4. The importance of scale

Considering these different pathways to resistance at a landscape scale highlights a range of current opportunities, particularly how and where wildfires can be leveraged. This can include smaller stand-scale treatments, particularly where there are values to protect. These more traditional treatment-scales are also valuable because when they collectively cover 25–40 % of a large landscape (>274,000 ha), they can reduce wildfire frequency and severity across the entire landscape (Povak et al., 2023, Finney, 2007). Ideally > 40 % of a large landscape would be in a *maintain* pathway to reduce the probability of large and severe fires under even the most extreme weather (Povak et al., 2023).

A landscape scale perspective can also support larger scale management actions such as prescribed fire and RO wildfire by helping to determine priorities and limitations. For example, a low elevation POD with no current resistance to high-severity fire (e.g., where the management need is a first-entry treatment to *create* some resistance) would not be a strong candidate for RO wildfire under hot and dry conditions, when fire effects would likely be severe and there is a high risk of escaping planned boundaries. However, in a POD where the primary pathway is maintaining resistance, it may be appropriate to manage fire even under warmer and drier conditions. Under the right conditions for the situation, landscape scale prescribed and RO wildfire can be used to treat a variety of initial conditions, addressing all three pathways to resistance (*create*, *enhance*, *maintain*) and contributing to a pyrodiverse landscape.

RO wildfire to increase resistance would likely be applied at the POD scale. Implementing RO wildfire is likely initially the most feasible in designated Wilderness areas and in areas where agencies have determined that fire poses little risk to communities and infrastructure, would likely benefit natural resources, and when conditions are suitable and it is safe to implement (e.g., Wildfire Maintenance Zones on the Inyo, Sierra, and Sequoia National Forests)(US Forest Service, 2019, 2023a, 2023b). In addition, Strategic Fire Zones were recently proposed as additional areas where fire may post little risk to assets. These zones are characterized by large, contiguous areas (>2000 ha) of frequent fire-adapted forest with no infrastructure that are located on national forest lands outside of Wilderness areas (North et al., 2024). Vegetation

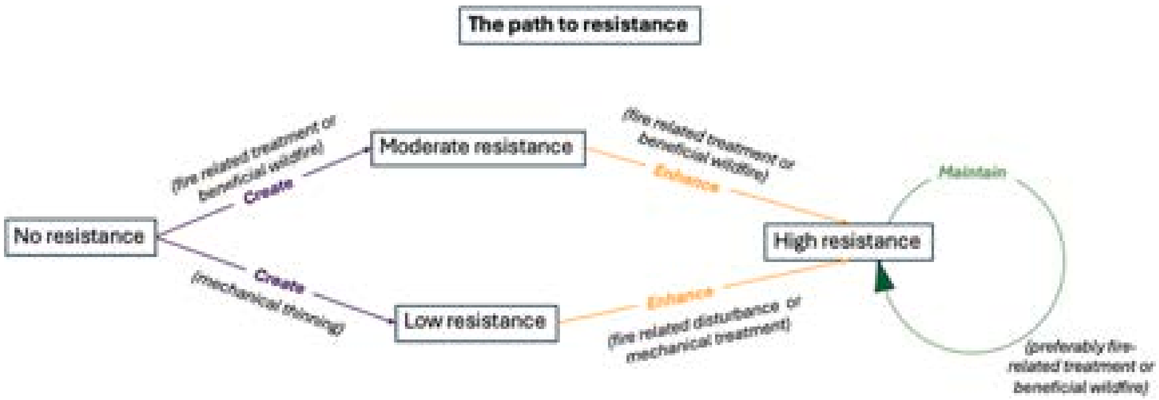

Fig. 1. Re-establishing resistance to high-severity wildfire in frequent-fire adapted forests: along the path to resistance, forest managers can take different pathways to *create, enhance*, or *maintain* resistance, depending on the starting condition. Even high resistance areas need to be maintained with fire-related treatment, including prescribed fire or RO wildfire, to continue to be resistant to future high-severity wildfire.

Table 2
Area of opportunity for the three management pathways, where the pathways apply relative to wildfire footprints, and based on past disturbance history.

Management pathway	Position relative to wildfire footprint	Disturbance history (10-yr)	Area (ha)	# PODs with > 202 ha
Create	Adjacent	None	236,757	197
Create	Inside	Unburned islands	3130	4
Enhance	Adjacent	One mechanical treatment	42,829	61
Enhance	Inside	Mechanically-treated islands	771	1
Enhance	Inside	One beneficial wildfire	299,884	301
Maintain	Inside	Two or more beneficial disturbances, one is fire	102,699	164
Maintain or enhance (≥25 % in maintain and >405 ha combined)	Inside or Adjacent	One mechanical treatment, Mechanically-treated islands, One beneficial fire, Two or more beneficial disturbances, one is fire	104,461	95*

*PODs with > 405 ha combined *maintain* or *enhance*.

in these zones could be strategically treated and managed so that a wildfire burning under the right conditions would burn across its extent with spatially variable fire effects and no harm to human or biological assets.

3. Case study

To identify opportunities to *create*, *enhance* and *maintain* resistance by leveraging wildfire footprints, we use the Sierra Nevada of California as a case study. We quantify these opportunities across 1673 PODs in the Sierra Nevada that range in size from 10 to 49,759 ha (median = 2352 ha) enabling a landscape level approach. We focus on the Sierra Nevada because of its wealth of data and geographic and ecological cohesiveness, but similar conditions and management choices are common in many western US forests. We mapped the pathways based on past disturbances including wildfire or treatment. We were particularly interested in identifying the largest scale opportunities, the potential cost-savings from using existing containment lines, and the likely lower risk places to scale up prescribed fire projects and RO wildfire. Our goal is to translate established science into a spatially actionable, data-driven management plan that can increase pace and scale, reduce operational risk under suitable conditions, and promote pyrodiversity and biodiversity.

3.1. Mapping the opportunity

To map the opportunity, we relied on a dataset compiled by Shive et al. (2025) that inferred the degree of resistance to high-severity fire (as of 2022) from disturbance histories across yellow pine-mixed conifer forests in California's Sierra Nevada. The resistance classes are based on established relationships between past disturbance and resistance to high-severity fire. Areas that experienced at least two beneficial disturbances, which could include beneficial wildfire, prescribed fire, or mechanical treatment, with at least one disturbance being fire, were classified as High resistance. Areas with only one prescribed fire or beneficial wildfire were classified as Moderate resistance, and since mechanical treatments on their own do not confer as much resistance as the fire-related treatments of prescribed fire, pile burning, or beneficial wildfire, these areas were classified as Low resistance (Table 1).

We did not classify the resistance of areas burned at high severity, as these likely lost forest cover that would not recover mature trees for decades or could be at risk of type conversion. Our emphasis is on areas that have retained a live, mature forest. Shive et al. (2025) used an optimistic timeline (22 years, 2001–2022) in their consideration of past disturbances, which is two times the mean fire return interval of the dry mixed conifer forest type (van de Water & Safford 2011). Beyond 22 years, fuels accumulate such that the risk of high-severity fire and crown fire dramatically increases (North et al., 2021, Steel et al., 2015). We took a more conservative approach based on recent work by Davis et al. (2024), which suggests that fuel treatment longevity is closer to ten years, and focused our case study on disturbances that occurred from 2013 to 2022. The resistance classes directly map to the three resistance pathways described above (Table 1). There are a range of opportunities to shift forest stands towards the High resistance class (Fig. 1). *Creating* to *enhancing* and then *maintaining* stands can be thought of as moving along a path of no to High resistance that ultimately leads to High resistance (Fig. 1). Keeping a range of management options open, from utilizing recent wildfires to *create* resilience in the short term (<3 years with minimal preparation of the containment line), to *enhance* in the near term (3–10 years), and *maintain* after 10 + years, provides managers with alternatives to solely focusing on long-unburned forests.

We quantified the strategies at the POD scale because landscape-scale treatments, specifically large-scale prescribed fire and RO wildfire, are likely to have the biggest impacts. We used the resistance classifications to map the opportunities to *create*, *enhance*, and *maintain*

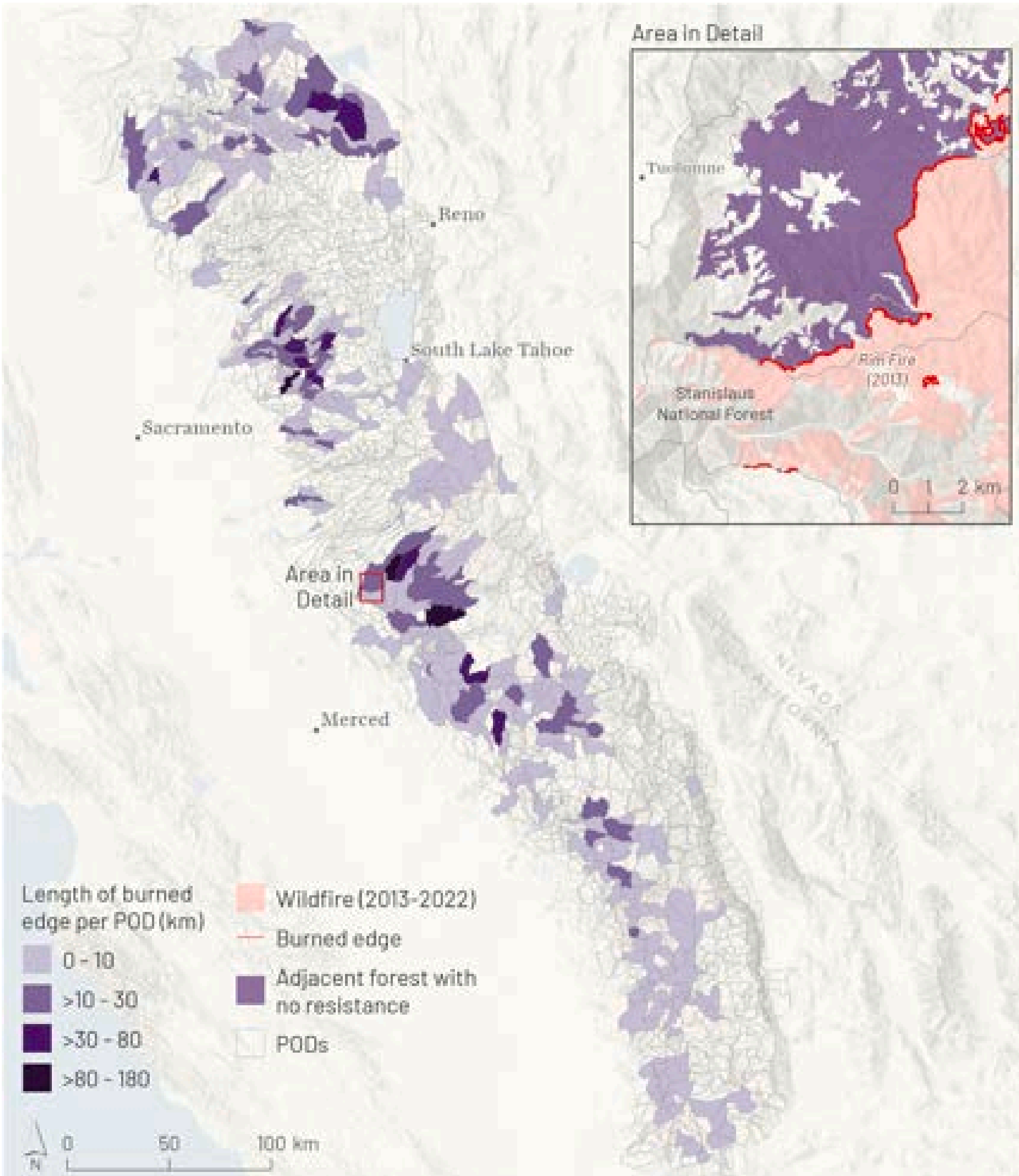

Fig. 2. PODs symbolized by length of edge burned in wildfires from 2013 to 2022 and adjacent to unburned yellow pine and mixed conifer forests.

resistance. For the *create* pathway, we identified burned edges with adjacent yellow pine-mixed conifer forest with no resistance. We set a minimum burned edge length of 450 m to match the median size of the edge of a recent prescribed fire project (20 ha) assuming a square shape. We calculated the area of forest with no resistance that was adjacent to the burned edge, extending out to a maximum distance of the POD edge. We also identified untreated/unburned islands of yellow pine-mixed conifer forest completely within a wildfire footprint not entirely adjacent to burned edges, again with a minimum size of 20 ha (Fig. 3).

To estimate the economic value of using fuel-reduced areas produced by wildfires as containment lines, we calculated how much it would cost to construct new line on these areas. While it is unlikely that using wildfires as containment lines would eliminate all burn preparation needs and costs, it could substantially reduce them. We summed the length of burned edge and estimated what that year's fire line would have cost if constructed by a 20-person Interagency Hotshot crew (Type 1 IHC). We used published estimates for the crew cost in timbered areas (fuel model 8–10), averaging indirect and direct line construction rates (Dodson and Mitchell 2016, NWCG 2021). We adjusted the average cost to account for inflation using the Consumer Price Index. The cost was $67.25 per chain (20 m; 66 feet) in 2015 dollars ($1 per foot), equivalent to $92.96 per chain in 2025 dollars or $4625 per kilometer. We did not estimate the costs savings as there was no data available for the cost of prepping a burned edge to be used as a containment line.

To map the *enhance* pathway, we identified mechanically-treated forests classified as Low resistance (one mechanical treatment adjacent to a wildfire footprint plus mechanically-treated islands) that were adjacent to burned edges (less than three years old) or completely within a wildfire footprint, as well as forests classified as Moderate resistance (one instance of beneficial fire within a wildfire footprint). We

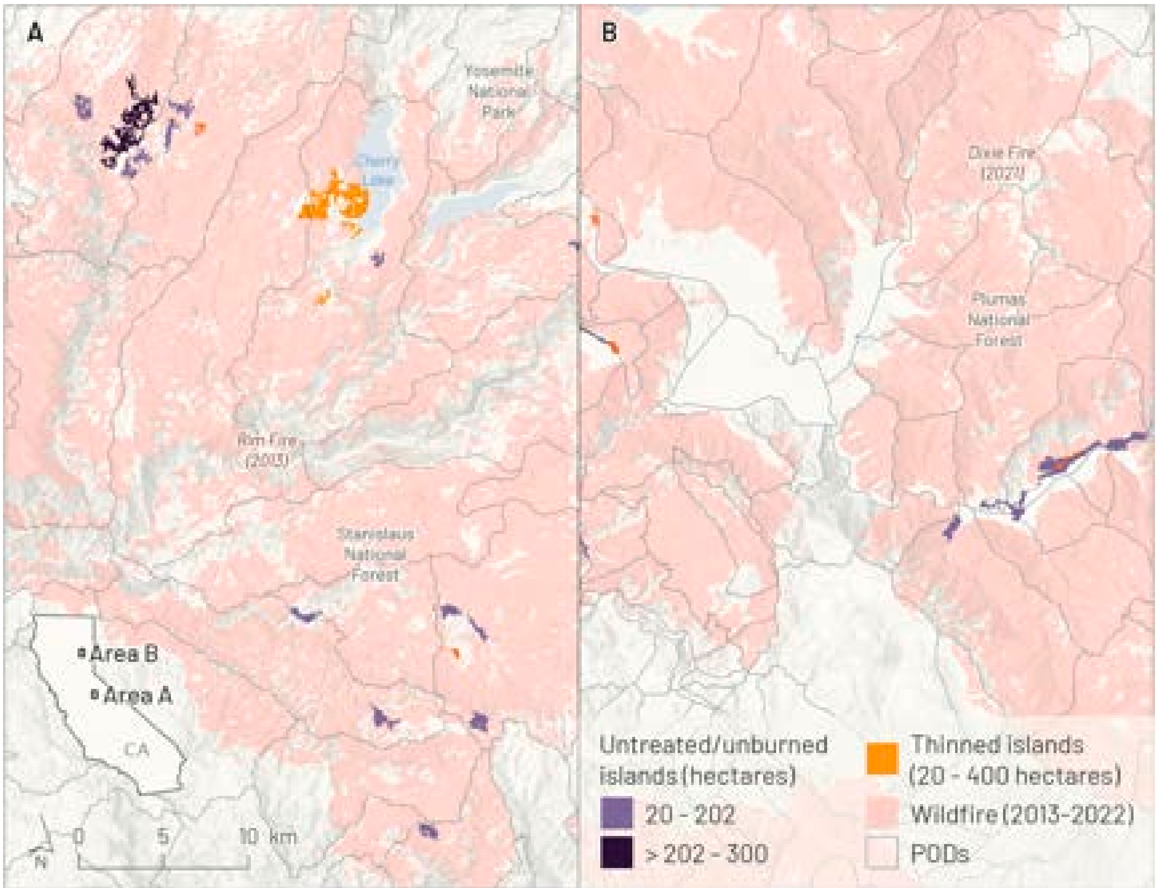

Fig. 3. Untreated/unburned islands *(create* pathway*)* and thinned islands *(enhance* pathway*)* as of 2022 that are surrounded by burned edges inside the 2013 Rim Fire footprint (A) and 2021 Dixie Fire footprint (B). Minimum island size is set based on the median size of recent prescribed fire projects (2001–2022).

calculated the mechanically-treated area that was adjacent to the burned edge, extending out to a maximum distance of the POD edge. To map the *maintain* pathway, we used areas classified as High resistance (where two or more disturbances, one being beneficial wildfire or prescribed fire, have occurred). We then calculated the total forest area in the *enhance* and *maintain* pathways in each POD. We also recorded the majority ownership of the POD as protected (includes public lands and conservation ownership), private timber, or private other (Table S1). Ownership information can inform the feasibility, with the presence of private owners and mixed ownership potentially making prescribed fire and RO wildfire more challenging to implement.

To focus on the largest scale opportunities, we identified a subset of PODs where there is ≥ 25 % of forest in *maintain*, the minimum threshold identified to reduce future fire severity in large landscapes (Povak et al., 2023). In these "maintain PODs," we also set a minimum threshold of ≥ 405 ha of combined hectares of *enhance* and *maintain*. Finally, we identified the spatial overlap of "maintain PODs" with fire zones (Wilderness Areas, Wildfire maintenance zones, and Strategic Fire Zones) where managed fire could be easier to implement.

3.2. Quantifying the opportunity

There is an opportunity to *create* resistance on more than 230,000 ha across 197 PODs of untreated and unburned forest adjacent to wildfire footprints by using the burned edge as a control line (Table 2, Fig. 2, Supplementary Table 1). The median length of burned edge per POD was 3.3 km and total length across the entire area was 3258 km. The entire length of burned edge would have cost ~$16 M to construct in 2025. Inside wildfire footprints there were 57 untreated/unburned islands with a maximum size of 293 ha, which is 14 times as large as the median size of recent prescribed fire projects (20 ha). Over 40 % of the islands were twice as large as the median size of prescribed fire projects. Managers could implement a mechanical treatment if needed and burn these islands to *create* resistance across 3130 ha (4 PODs) by using the surrounding burned area as containment lines (Fig. 3).

The largest scale opportunity is to *enhance* forests inside and adjacent to wildfire footprints (Table 2). Almost 300,000 ha across 301 PODs have had one beneficial wildfire and could be treated to move these forests into a high resistance condition. There are also 42,829 ha with one mechanical treatment adjacent to a wildfire footprint. We found 7 mechanically-treated islands with a maximum size of 357 ha, 18 times the size of recent prescribed fire projects. There are more than 100,000 ha (164 PODs) with two or more beneficial disturbances and high resistance.

We identified 95 "maintain PODs" that have ≥ 25 % in high resistance forest with at least 405 ha combined to *enhance* and *maintain* (Fig. 4). These PODs are distributed throughout the ecoregion with a concentration in the north where the Dixie Fire burned in 2021. Majority ownership of these maintain PODs is predominately U.S. Forest Service followed by Private Timber, Private Other, and National Park Service. Six of these PODs had more than 90 % overlap of *maintain* and *enhance* area with fire zones and were located within Sequoia National Park, Eldorado National Forest, and Plumas National Forest.

4. Regulatory pathways and hurdles

There are a few regulatory pathways either in place or proposed that can readily support leveraging wildfire footprints. Environmental compliance under the National Environmental Policy Act (1969), NEPA) requires analyses of the potential environmental impact of projects

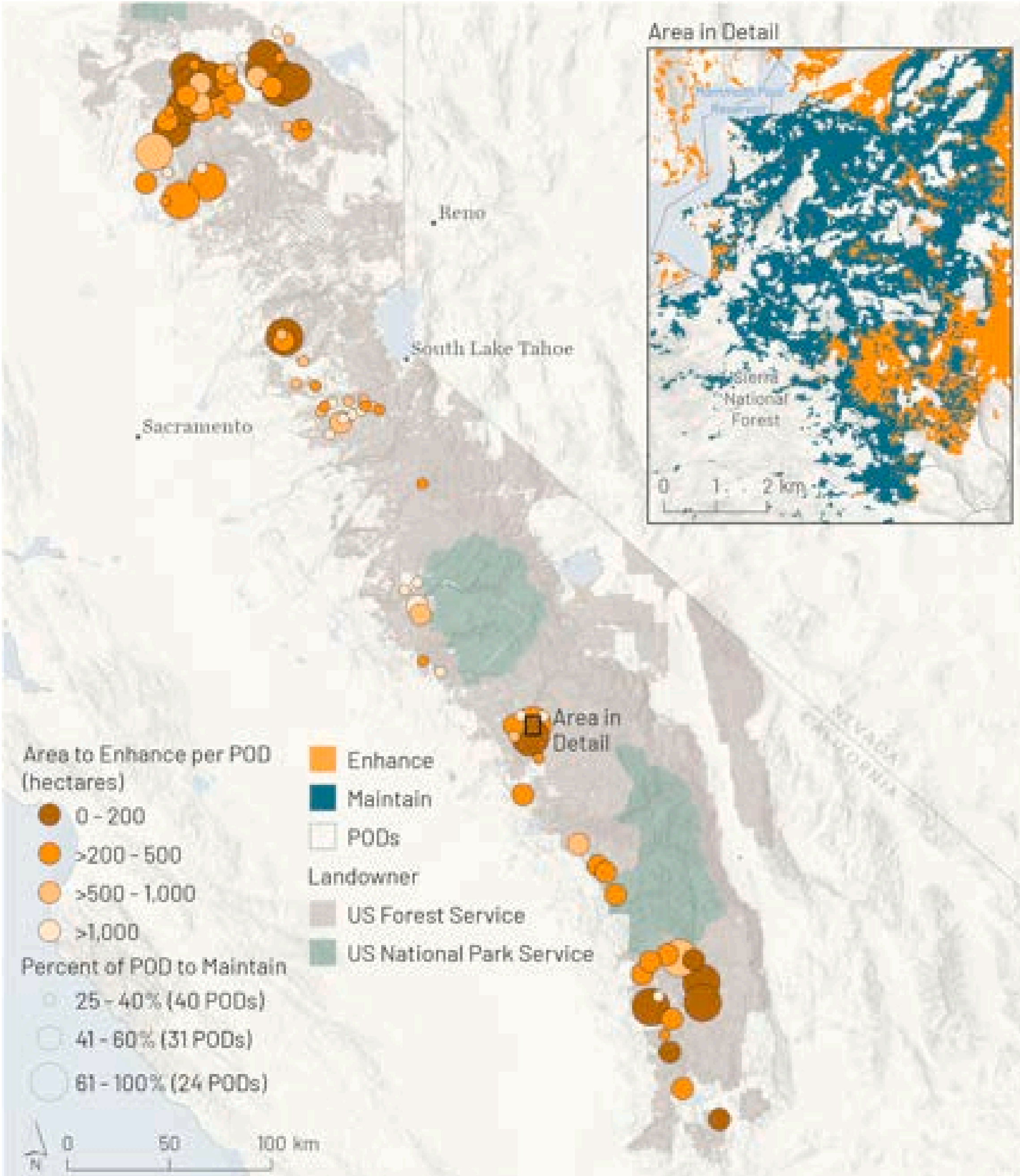

Fig. 4. PODs (n = 95), represented as circles, with at least 405 ha to *enhance* and *maintain* and with a minimum of 25 % *maintain*. Larger circles correspond to a larger percent of *maintain* in a POD, and darker orange represents fewer hectares to *enhance* within a POD to move it into a *maintain* pathway. Map legend includes the number of PODs in each percent range.

conducted on public lands. At present, most National Forests need to generate new NEPA analyses for each prescribed fire project, which can be costly and time consuming. The National Park Service in many areas has long relied on programmatic NEPA documents that analyzed the impacts of prescribed fire park-wide (National Park Service 2004, 2005a), which allows them to implement prescribed fire more efficiently. National Forests are increasingly adopting this model for prescribed fire, with the Sequoia and Sierra National Forest and Humboldt Toiyabe National Forest Forestwide Prescribed Fire Projects that allow for prescribed fire across these management units, except for wilderness areas in the Humboldt Toiyabe (US Forest Service 2025a, 2025b). The Klamath and Shasta-Trinity Prescribed Fire Project is another effort to streamline compliance that is currently in review. Yosemite and Sequoia and Kings Canyon National Parks Fire Management Plans (National Park Service 2005b, 2005c) have also specified where RO wildfire can be used, an approach being increasingly adopted by National Forests. The Sierra, Sequoia, and Inyo National Forests have identified wildfire maintenance zones and wildfire restoration zones in their updated forest plans which designate space for RO wildfire when conditions are suitable (North et al., 2021). There are also proposed changes to permitted activities (categorical exclusions) on national forests that allow mechanical treatments and prescribed fire to reduce fire hazard with no area limit, and post-fire salvage of dead or dying trees on < 101 ha without going through the NEPA process of analysis, proposed agency action, decision, and public comment periods. While these changes could streamline post-fire management activities on national forests, it is too soon to tell if they will be acted on.

The above advances notwithstanding, there are additional policy and legal challenges that need to be addressed to allow more prescribed fire and RO wildfire in wildfire footprints. Specifically, environmental compliance (NEPA, Endangered Species Act, and Clean Air Act) slows down implementation and adds to the cost. A more efficient and defensible approach would be to exempt prescribed fire, cultural burns, and RO wildfire from environmental compliance, given that fire is a keystone process implemented over millennia by people (Clark et al., 2024). Clean Air Act regulations should be revised to designate all prescribed fire as "exceptional" emissions that, like wildfires and some prescribed fire, do not count toward a state's air quality standards. Along the same vein, regulations in wilderness that are specific to different agencies and individual Wilderness Areas need to be revised to make prescribed fire and RO wildfire easier to implement (Boerigter et al., 2024). Finally, there could be financial incentives such as carbon credits and a carbon accounting protocol changes that account for the benefits of prescribed fire in terms of reducing the risk of high-severity fire (e.g. buffer pool).

5. Applications

While we focused on the Sierra Nevada as a case study, the three pathways apply to all frequent-fire, dry conifer forests across western North America. We suspect that this pattern of wildfire doing most of the fuel reduction work compared to mechanical treatments or prescribed fire treatments is repeated across the western U.S. As the backlog of forests in need of restorative fire grows, we are simultaneously losing large areas of mature forest to high-severity fire (Steel et al., 2023) and not leveraging the beneficial effects created within wildfire footprints. If we do not adopt a more diverse portfolio of approaches to address the wildfire crisis, including leveraging wildfires, we will fall further behind, creating conditions that will likely lead to more large, high-severity wildfires.

Compared to the work required to return long unburned forest stands to a state of high wildfire resilience, leveraging wildfire footprints offers important opportunities that are more cost effective and, in many cases, involve less risk. When other projects get delayed or are subject to indefinite postponement because of dense fuels or other fire escape-related risks, burned footprints could be a viable alternative option. Further, identifying PODs that can be maintained with fire because they already possess some degree of resistance to future high-severity fire may increase the area where RO wildfire is considered a viable option. Although the potential benefits of the three pathways presented here have not yet been quantified, future demonstration projects could test these ideas by tracking and quantifying how each one impacts operational risk, cost, and biodiversity.

Variously creating, enhancing and maintaining resistance will ultimately lead to a more pyrodiverse landscape that provides a wider array of niches and successional pathways than homogeneously burned or unburned areas, increasing alpha and beta diversity across the landscape (Tingley et al., 2016, Miller and Safford, 2020, Jones and Tingley, 2022, Ulyshen et al., 2022). When a reburn sweeps through, flames interact with residual fuels, snags, and regenerating vegetation, effectively burning a mosaic within the mosaic and layering new severity classes onto the previous burned area. Areas burned with frequent low-to-moderate severity fire sustain higher native-plant richness, a more heterogeneous understory, and when high-severity patches are limited support higher occupancy by Mexican spotted owl pairs (Odland et al., 2021, Jones et al., 2024). Collectively, these lines of evidence suggest that layering beneficial fire onto recent burn footprints builds a patchy, fire-adapted landscape of structural and compositional diversity, including meadows, grasslands, and shrub fields (Boisramé et al. 2017) that surpasses what a single entry in a long fire-excluded forest can achieve.

Re-establishing frequent fire and a patchy burned mosaic will require new approaches. We contend that leveraging the beneficial work of recent wildfire has the potential to expand the area treated while reducing costs and risk. By focusing management on keeping fuels low and using burned edges to treat adjacent areas in the years immediately following wildfire, this approach could help to break the cycle of high-severity fire impacts and restore native fire regimes.

CRediT authorship contribution statement

Kristen N. Wilson: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Conceptualization. **Kristen L. Shive:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **J. Nicholas Hendershot:** Writing – review & editing, Writing – original draft, Methodology. **Michelle Coppoletta:** Writing – review & editing, Methodology. **Malcolm P. North:** Writing – review & editing, Methodology. **John N. Williams:** Writing – review & editing, Writing – original draft, Methodology. **Charlotte K. Stanley:** Writing – review & editing, Visualization, Investigation, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.123443.

Data availability

https://osf.io/xvj6p

The pace and scale challenge: Leveraging wildfire footprints to increase forest resilience to future high-severity fire (OSF)

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