Received: 9 October 2024 | Revised: 25 March 2025 | Accepted: 22 April 2025

DOI: 10.1002/ecs2.70306

ECOSPHERE
AN ESA OPEN ACCESS JOURNAL

ARTICLE

Vegetation Ecology

Leveraging wildfire to augment forest management and amplify forest resilience

Kristen L. Shive[1] | **Clarke A. Knight**[2] | **Zachary L. Steel**[3] | **Charlotte K. Stanley**[4] | **Kristen N. Wilson**[4]

[1]Department of Environmental Science, Policy and Management, University of California, Berkeley, Berkeley, California, USA

[2]U.S. Geological Survey, Mountain View, California, USA

[3]U.S. Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA

[4]The Nature Conservancy, San Francisco, California, USA

Correspondence
Kristen L. Shive
Email: kshive@berkeley.edu

Handling Editor: Franco Biondi

Abstract

Successive catastrophic wildfire seasons in western North America have escalated the urgency around reducing fire risk to communities and ecosystems. In historically frequent-fire forests, fuel buildup as a result of fire exclusion is contributing to increased fire severity. The probability of high-severity fire can be reduced by active forest management that reduces fuels, prompting federal and state agencies to commit significant resources to increase the pace and scale of fuel reduction treatments. However, lower severity areas of wildfires also have the potential to act as "treatments," and even catastrophic fires with large areas of high severity can still have substantial areas of lower severity fire that may be improving forest conditions locally. We quantified active management and wildfire severity across yellow pine and mixed conifer (YPMC) forests in the Sierra Nevada of California over a 22-year period (2001–2022). We did not detect increases in the area treated through time, but the area of beneficial wildfire (low to moderate severity) increased substantially, exceeding active treatment area in 8 of 22 years. Overall, beneficial wildfire treated ~17% more area than all treatments combined, and roughly four times more area than fire-related treatments alone. We then used disturbance history to evaluate resistance to high-severity wildfire and forest loss across the YPMC range. Of the 2.3 million ha YPMC of forests in 2001, 20% lost mature forests due to high-severity fire by 2022, which is nearly half of all YPMC area burned. Most of the landscape (47%) remains at risk of high-severity fire because it had no restorative disturbances, but 33% of the study area has some level of resistance to high-severity wildfire. In these areas, resistance will need to be enhanced and maintained over time via active management or managed wildfire, but these treatment needs will likely outpace capacity even under optimistic implementation scenarios. Given limited resources for implementing active management and the likelihood of a more fiery future, incorporating beneficial wildfire into landscape-level treatment planning has the potential to amplify the impact of active management treatments.

KEYWORDS
beneficial wildfire, fire severity, forest resilience, fuel treatments

INTRODUCTION

Increasing wildfire activity and severity in the western United States has escalated public and political urgency to reduce fire risk to communities and ecosystems (California Wildfire and Forest Resilience Task Force, 2022a; State of California, 2020; U.S. Forest Service, 2022a). Although the warming climate contributes to these trends (Abatzoglou & Williams, 2016; Parks & Abatzoglou, 2020), fuel buildup from fire exclusion also plays an important role in the dry conifer forests of this region (Miller, Safford, et al., 2009; Steel et al., 2015). These forests historically experienced frequent, low- to moderate-severity fire that kept tree densities and woody fuel loads relatively low (Hagmann et al., 2021), but surface and ladder fuels have increased beyond the historic range of variability for these ecosystems, contributing to high-severity fire effects when wildfires occur (Parks & Abatzoglou, 2020; Safford & Stevens, 2017; Williams et al., 2023). Extensive high-severity fire can contribute to the deterioration of watershed function and downstream impacts (Belongia et al., 2023), loss of mature forests (Shive et al., 2022; Steel et al., 2023), reduced biodiversity (Steel et al., 2022; Weeks et al., 2023), and limited postfire forest regeneration (Davis et al., 2023; Shive et al., 2018; Welch et al., 2016).

Fuel treatments such as prescribed fire and mechanical treatments that reduce woody surface fuels and tree densities (e.g., ladder fuels) can reduce the severity of a subsequent wildfire (Brodie et al., 2024; Kalies & Yocom Kent, 2016; Stephens et al., 2009). Mechanical treatments that additionally target some larger, merchantable trees can also play a role by reducing canopy fuels and overall tree density, while helping to meet broader habitat restoration goals and potentially reducing the impacts of drought and beetles (Fettig et al., 2022; Stephens et al., 2024; Young et al., 2017). While all of these tools are important for promoting healthy, resilient forests, the combination of prescribed fire and mechanical treatments is the most effective at reducing fire severity, and prescribed fire is more effective than mechanical thinning when they are applied in isolation (Brodie et al., 2024; Davis et al., 2024; Kalies & Yocom Kent, 2016; Prichard et al., 2010, 2020; Tubbesing et al., 2019).

Given the efficacy of these treatments in forestalling catastrophic wildfires, State and Federal government entities have committed significant resources to increase the pace and scale of implementation (State of California, 2022; U.S. Department of the Interior, 2024; U.S. Forest Service, 2022b). In California, efforts include an ambitious federal-state partnership, with the State and the U.S. Forest Service (USFS) committed to treating 404,686 ha (one million acres) annually by 2025 (California Wildfire and Forest Resilience Task Force, 2022a). To meet this goal, agencies are funding specific projects, establishing more fuel management-related positions, and developing programs to increase the skilled workforce in private industry (California Forest Management Task Force, 2021; California Wildfire and Forest Resilience Task Force, 2024; Sadek, 2024). Despite these efforts, California was still far below the one-million-acre goal as of 2019 (Knight et al., 2022).

Concurrently, there is increasing recognition that wildfires themselves have the potential to act as a "treatment." In California's Sierra Nevada, federal agencies (primarily the National Park Service [NPS]) have been managing wildfire for resource benefit in some wilderness areas for decades (Stephens et al., 2021; Van Wagtendonk & Lutz, 2007). These are lightning-ignited wildfires that are managed for resource and fuel reduction benefits when weather conditions are likely to result in desirable fire effects. There are rising calls for increasing the use of managed wildfire (Prichard et al., 2021; Wu et al., 2023) including on large portions of U.S. Forest Service lands (North et al., 2024).

Yet even within wildfires managed for suppression and that have large patches of high severity, there can be substantial areas that burned at low to moderate severity. Similar to a prescribed fire, these lower severity areas can have restorative effects (Churchill et al., 2022; Larson et al., 2022; Meyer et al., 2021; Stevens et al., 2021). Although postfire conditions in these lower severity classes vary (Miller & Thode, 2007), the landscape generally benefits from surface fuel reductions (Collins et al., 2016; Das et al., 2025) similar to a prescribed fire, while retaining mature, live trees (Miller, Knapp, et al., 2009). Maintaining these surviving forests on the landscape can have more immediate habitat, water, and carbon benefits than reforesting high-severity areas (Moomaw et al., 2019).

Capitalizing on these initial wildfire treatments could also have significant practical benefits for forest managers. Depending on the degree of fuel consumption, these areas may not need another treatment for years, giving managers time to prioritize treatments and conduct the required state and federal assessments (e.g., National

Environmental Protection Act). In contrast, in fuel-loaded, unburned forests, managers are often racing against the clock to complete the planning work and treatments before they burn in a wildfire. Forest managers could also use recently burned areas to facilitate the implementation of prescribed fire. Since recent fires can constrain adjacent fire spread (Collins et al., 2009), burning adjacent to areas with significant fuel consumption (e.g., "good black") could reduce the potential for escapes. Despite these potential benefits, postfire management and the associated planning and compliance have generally focused on salvage logging and planting in high-severity areas (Larson et al., 2022). Recent work proposes an integrated approach that includes consideration of areas that may have had beneficial fire on USFS lands (Meyer et al., 2021), but this has yet to be widely adopted.

We used trends in treatment and wildfire in the yellow pine and mixed conifer (YPMC) forests of California's Sierra Nevada as a case study in how wildfire and treatments are impacting historically frequent-fire forests. We explored a 22-year period (2001–2022), which spans a conservative estimate of the amount of time it takes for fuels to reaccumulate after a fuel-reducing activity (North et al., 2012). Specifically, we

1. examine trends in forest treatments by type and ownership, to explore whether the recent push to increase "pace and scale" is detectable;
2. compare these trends to wildfire area burned, particularly to the area burned with potentially beneficial effects (low and moderate severity);
3. consider how forest treatments and wildfires have interacted to shape the current state of the range, including forest resistance to severe wildfire; and
4. explore future treatment needs to maintain existing resistance to high-severity fire.

METHODS

Study area

Our study area is comprised of the YPMC forests of the Sierra Nevada mountains in California and Nevada, USA. YPMC forests are dominated by ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson), white fir (*Abies concolor* (Gordon & Glend.) Lindl. ex Hildebr.), incense cedar (*Calocedrus decurrens* (Torr.) Florin), sugar pine (*Pinus lambertiana* Douglas), Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.), Pacific Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), and California black oak (*Quercus kelloggii* Newb.). The climate is Mediterranean, with most of the precipitation falling as snow in the winter, with hot, dry summers (North et al., 2016). We used a 22-year window as our study period, which is based on previous work that suggests that uncharacteristically high fuel accumulation (North et al., 2012) and, consequently, greater vulnerability to severe fire (Steel et al., 2015) occurs by roughly twice the mean reference return interval for a given forest type (e.g., 2×11 years for dry mixed conifer; Van de Water & Safford, 2011).

Vegetation data

To best approximate YPMC forested area at the beginning of our analysis period (2001), we used a vegetation dataset from 2000 for most of the study area created by the USFS Remote Sensing Lab (hereafter, CALVEG2000; U.S. Forest Service, 2000). Spatial data were processed and analyzed in ArcGIS Pro 3.3 (Esri, 2024). We removed all areas of high-severity wildfire that occurred in 2000 to create a baseline forest dataset for 2001.

CALVEG2000 did not include non-USFS lands, so we supplemented it with the current CALVEG for the northern and southern Sierra Nevada regions, which was primarily classified with 2001 imagery, though some areas used later imagery (U.S. Forest Service, 2018a, 2019). We explored the potential impact of areas with more recent imagery on our characterization of the 2001 distribution of YPMC forests, finding that it impacted <0.1% of the area (see Appendix S1). We used the CALVEG "Vegtype" classification system because it was included in both datasets. Table 1 lists the vegetation types that we included in our YPMC forest type, which yielded 2,259,901 ha of YPMC forest in the year 2001 (covering 43% of the Sierra Nevada Ecoregion).

Land ownership data

We used the 2022 California Protected Areas Database (GreenInfo Network, 2022) and Nevada Protected Areas Database (U.S. Geological Survey Gap Analysis Project, 2024) to identify ownership across YPMC forests. We classified the NPS, USFS and BLM individually because they manage so much forest area in the Sierra Nevada, but lumped remaining federal agencies as "Other federal agencies." We then grouped all state agencies together and created an "Other" category for small holdings by local entities (e.g., City and County governments, Irrigation Districts). The remainder of the YPMC forested area was classified as private land (ParcelQuest, 2023; Regrid, 2023), which includes nonprofits, small private forest landowners and industrial timber companies, which we lumped since they are all subject to California Forest Practice Rules

TABLE 1 CALVEG vegetation types (U.S. Forest Service, 2000) that were included as yellow pine and mixed conifer (YPMC) forest, including the source version.

CALVEG type code	CALVEG name	CALVEG version
BT	Big Tree	Both (CALVEG99, current CALVEG)
DP	Douglas-Fir–Pine	Both
EP	Eastside Pine	Both
PD	Gray Pine	Both
JP	Jeffrey Pine	Both
MF	Mixed Conifer–Fir	Both
MB	Mixed Conifer–Giant Sequoia	Both
MP	Mixed Conifer–Pine	Both
DF	Pacific Douglas-Fir	Both
PP	Ponderosa Pine	Both
PW	Ponderosa Pine–White Fir Alliance	Current CALVEG
MD	Incense Cedar Alliance	Current CALVEG
WF	White Fir	Both

(CAL FIRE, 2024). The analysis of parcel data suggests that at least 228,023 ha of the 646,526 ha of private land are managed by industrial timber operators. However, the actual number is likely somewhat higher because parcels owned by an individual company can be registered under different names; given that, we present all private land data together.

Fire severity data

For 2001–2017, we used the USFS Region 5 Vegetation Burn Severity database (U.S. Forest Service, 2018b), which derived fire severity within wildfire perimeters from Landsat Thematic Mapper satellite imagery using the Relative differenced Normalized Burn Ratio (RdNBR) (Miller & Thode, 2007). RdNBR was subsequently classified into severity classes using field-calibrated thresholds for the region: undetected change/unburned (no change), low (1%–25% loss of live vegetation), moderate (26%–75% loss of live vegetation), high (76%–100% loss of live vegetation; Miller & Thode, 2007). The Region 5 database does not extend beyond 2017, so we used Google Earth Engine to generate severity maps for 2018–2022 (Parks et al., 2018). A comparison of 50 randomly selected fires from 1985 to 2017 showed high similarity between the two approaches, supporting their combined use for wildfire severity tracking (Williams et al., 2023). The combined severity database included all fires >81 ha (200 acres, the threshold for inclusion in the USFS Fire Severity database), resulting in 420 wildfires. Although the "undetected change" category can include areas where surface fuels were reduced by a light underburn, we excluded it from our analysis because it is often fully unburned (Miller & Thode, 2007). We also used these data to quantify the area inside high-severity patches that may be seed-limited and at risk of regeneration failure (Davis et al., 2023; Shive et al., 2018) by calculating the total area that exceeded expected seed dispersal distance from a live tree (i.e., 61 m; McDonald, 1980), using lesser burned edges as a proxy for live tree seed sources (Shive et al., 2018).

To track only wildfires and treatments that occurred on forested landscapes, we adjusted the YPMC forest area annually by removing areas that had burned at high severity, as they are no longer forested. We implicitly assume no recruitment of mature forests in non-forested areas during our study period (22 years), given the slow successional timeline (~80 years to return to a mature forested state following severe disturbance; Russell et al., 1998).

Treatment data

We compiled several datasets of forest treatments from 2001 to 2022. For state and private lands, we used the Cal Fire Timber Harvest Plan databases (CAL FIRE, 2023a, 2023b), University of California Berkeley Research Forests Treatment data (obtained directly from the university), the state-assembled Interagency Tracking System (ITS) database (California Wildfire & Forest Resilience Task Force, 2023), and the prescribed fire database from Cal Fire's Forest and Range Assessment Program (FRAP) (CAL FIRE, 2023c) (note that the ITS database included only 2006–2022 due to data quality limitations before 2006).

For federal lands, we used agency compiled data. For the NPS, we used the Complete Treatment Perimeters database (NPS, 2024), which included 2002–2022, which we supplemented with data directly from each unit for 2001. We obtained BLM spatial data directly from the agency and associated treatment details from the National Fire Plan Operating System (U.S. Geological Survey, 2024), though BLM spatial data were only available for 2011–2022. The BLM only manages 1% of the 2001 YPMC footprint, so this omission likely had a negligible impact on our results. For the USFS, we obtained the timber harvest and hazardous fuels datasets from the USFS's Forest Activity Tracking System (FACTS) (https://data.fs.usda.gov/geodata/edw/) (US Forest Service, 2023a, 2023b). In R (R Core Team, 2023), the timber harvest and hazardous fuels datasets were cleaned and streamlined.

Specifically, activities not related to active forest management were removed (e.g., "Administrative Changes"), as were duplicative treatments, that is, the same management events on the same footprint of land in the same year were recorded once. We only included polygons that had a date in the "DATE_COMPLETED" attribute. For all federal sources, we excluded all "Fire Use" or other treatment types that refer to a wildfire that had resource benefit since these fires are more meaningfully represented in our fire severity dataset. Details on these datasets, their associated limitations, and any additional manipulations we did to refine the data are found in Appendix S1.

We reclassified all treatment types as either: "Fire-related treatment," which includes broadcast burning and pile burning, or "Mechanical treatment," which encompasses a wide range of forest treatments that are performed using heavy equipment or by crews using chainsaws (e.g., "hand thinning"), such as thinning strictly ladder fuels for fuel reduction goals, thinning merchantable trees to facilitate structural restoration or for profit, mastication, chipping, and many others. We lumped all of these treatments together because the different management agencies sometimes use the same designation for different treatments. For example, many USFS treatments that are driven by restoration goals may be classified as commercial thinning, but the effect of that treatment could be very different from commercially driven treatment on private lands. Thus, we simply make the distinction between process-based restoration and fuel reduction (fire-related treatment) and structural restoration or yield maximization (mechanical treatments). A detailed crosswalk of treatment types for all data sources is in Appendix S1: Table S1.

For the bar graphs summarizing treatment over time, we report "activity hectares," which refers to the total area treated for our treatment classes each year, regardless of whether or not it was treated again in other years. We made this choice because one of our interests is in understanding the total capacity to implement treatments in the region. Footprint hectares refers to the total area treated, regardless of the number of times different areas were treated; we report these in the text.

The State of the Sierra: Resistance classification

We classified the degree of resistance to high-severity fire across the YPMC range at the end of our study period based on the expected impact of the number and types of disturbances (treatment or wildfire by severity) within a given area, which was based on existing literature. Broadly, we consider low- to moderate-severity fire as beneficial wildfire. Conditions within these severity classes can vary substantially on the ground (Miller, Knapp, et al., 2009). However, surface fuels are an important driver of fire spread (Scott & Burgan, 2005) and they are generally reduced in both low- and moderate-severity areas (Collins et al., 2016; Das et al., 2025), so we made the simplifying assumption that these classes broadly meet targets for fuel reduction (Das et al., 2025; North et al., 2009; Safford & Stevens, 2017). In addition, the effects of mechanical thinning treatments on surface fuels can range from neutral to negative if they increase surface fuels. The impact of mechanical treatments generally depends on the specific treatment (Stephens et al., 2009), but since we lack detailed data on individual treatments, we made the simplifying assumption that they were neutral. This may overestimate their resistance to high-severity fire. We define restorative disturbances as areas with either beneficial wildfire or any of the three treatment classes described above.

Because the largest reductions in fire severity occur when thinning and burning treatments are combined (Brodie et al., 2024; Fulé et al., 2012; Prichard et al., 2010, 2020; Tubbesing et al., 2019), and that multiple low- to moderate-severity fires can help reach similar target conditions (Collins et al., 2016; Jeronimo et al., 2019; Steel et al., 2021), we defined High resistance as having at least two restorative disturbances, one of which must be either beneficial wildfire or fire-related treatment (i.e., prescribed fire or pile burning).

Where they occur in isolation, prescribed fires are more likely to reduce future fire severity than mechanical thinning-related treatments (Davis et al., 2024; Prichard et al., 2020), so we classified areas that had one fire-related treatment or beneficial wildfire as Moderate resistance. Areas that had one or more mechanical treatments were classified as Low resistance because they lack the critical surface fuel reduction (Davis et al., 2024). Areas with no disturbance during the 22-year time frame were designated as No resistance to high-severity fire.

Finally, we defined areas that burned one or more times at high severity as Mature forest loss (Davis et al., 2023; Shive et al., 2018). While some of these areas may have abundant natural regeneration or planted seedlings (Collins & Roller, 2013; Welch et al., 2016), we did not consider these areas as having "mature forests," since these conifers are relatively slow-growing, and the recolonization of forest habitat takes decades (Nagel & Taylor, 2005). We also calculated the total area that had short-interval high-severity reburns, as these areas may be at elevated risk of persistent type conversion (Coop et al., 2020).

All disturbances occurred within the study period, and we did not consider how disturbances before 2001 would impact resistance. We opted to not include treatments before 2001 primarily because federal treatment records predate modern mapping software and current quality control measures (Knight et al., 2022, supplement) and we wanted to be consistent between disturbance recording methods. To explore the potential impact this decision had on our results, we quantified the number of hectares that were either treated or burned at low–moderate-severity fire within our study period that also had a prior disturbance within the 22 years before the start of our study period. This occurred on ~9% of the area; while this is not insubstantial, since the effectiveness of treatments declines with time, focusing on repeated treatments within the study period is likely more important for inferences of resistance as of 2022.

We validated our resistance classification using geospatial data for the Sierra Nevada created by the USFS Accelerating Healthy Forests ("ACCEL") project, which relies on Forest Inventory and Analysis (FIA) data to reflect 2021 conditions (https://data.fs.usda.gov/geodata/rastergateway/accel/index.php). We compared the forested classes (No, Low, Moderate, or High Resistance) to the ACCEL estimated mean probability of high-severity fire for each class, as this metric most closely matches our classifications on resistance to high-severity fire. The probability of high-severity fire was derived from fire behavior models and predicts the probability of flame heights >2.4 m (8 ft) as outlined in Scott et al. (2013).

We also explored variation in resistance classes across the range for each hydrologic unit code 8 (HUC8) watershed (U.S. Geological Survey, 2023). At both the range-wide and watershed scales, we compared the percent YPMC with some level of resistance to a ~30% treatment target, since some work has suggested this as a minimum target to achieve landscape-scale reductions in fire severity (Ott et al., 2023).

We also conducted a thought exercise on future treatment needs to maintain existing resistance across the range. To get a conservative estimate of these maintenance needs, we assumed that all resistance classes would not need another treatment until the fuel treatment longevity maximum of 22 years (sensu North et al., 2012). For example, if 100 ha experienced its most recent restorative disturbance in 2020, we assumed that a maintenance treatment on those 100 ha would be needed in 2042. We projected these annual retreatment needs for the next 22 years and compared them to the annual average treatment rate to estimate how many years retreatment needs would be met.

RESULTS

Disturbance trends through time

Treatment type and rates varied greatly across the study period, but we did not observe a directional increase in YPMC treated area between 2001 and 2022 (Figure 1). Area treated peaked in 2008 (36,170 ha), driven by mechanical treatments, which averaged 16,879 ha annually, but markedly decreased after 2008. Fire-related treatments also varied through time, with an average of 5098 ha annually; these treatments were increasing in the early 2000s and then declined 2012–2016 and have fluctuated since.

Considering treatment by the land management group, NPS, USFS, and private landowners each treated at least 2000 ha total over the study period, with the majority of treatment by the USFS (282,730 activity ha) and private landowners (178,834 activity ha; Figure 2). For footprint hectares (the total land area receiving one or more treatments within the study period), the USFS treated 15% of the YPMC forest area under its management, and private landowners treated 22%. Mechanical treatments were by far the dominant treatment type on private lands, mostly commercial operations targeting timber extraction. Mechanical treatments also dominated on USFS lands, but there was substantially more fire-related treatment as well.

The NPS treated a total of 11,916 activity hectares over the study period, which covered 8% of their total YPMC area (i.e., footprint hectares). The 8% on NPS lands was almost all fire-related treatments, whereas fire-related treatments occurred on ~4% of USFS lands and <1% of private lands. Fire-related treatments were predominantly pile burning on USFS and private lands and broadcast burning on NPS lands. Mechanical treatments were limited on NPS lands but were more substantial after 2016.

Through time, mechanical treatments on private and USFS lands have fluctuated but remained well below 2008 levels, particularly in recent years. Mechanical treatments and fire-related treatments have fluctuated for the USFS and NPS over the study period, with slightly higher area treated with mechanical treatments on NPS lands in the last decade over the first decade. Mechanical treatments targeting strictly fuel reduction goals (e.g., chipping, mastication) and fire-related treatments increased slightly on private lands, and these treatments also made up the majority of area treated on state land (not shown), most of which occurred in 2020 and 2021. Most of the area treated on BLM land was mechanical treatment between 2018 and 2021 (but note we only have records for the BLM for 2011–2022).

In contrast, both wildfire area burned and severity increased markedly during our study period, resulting in accelerated loss of mature YPMC forests to high-severity fire (Figure 1). A total of 1,042,303 ha were classified as low-, moderate-, or high-severity fire effects (i.e., excluding the undetected change category) in the YPMC, with the

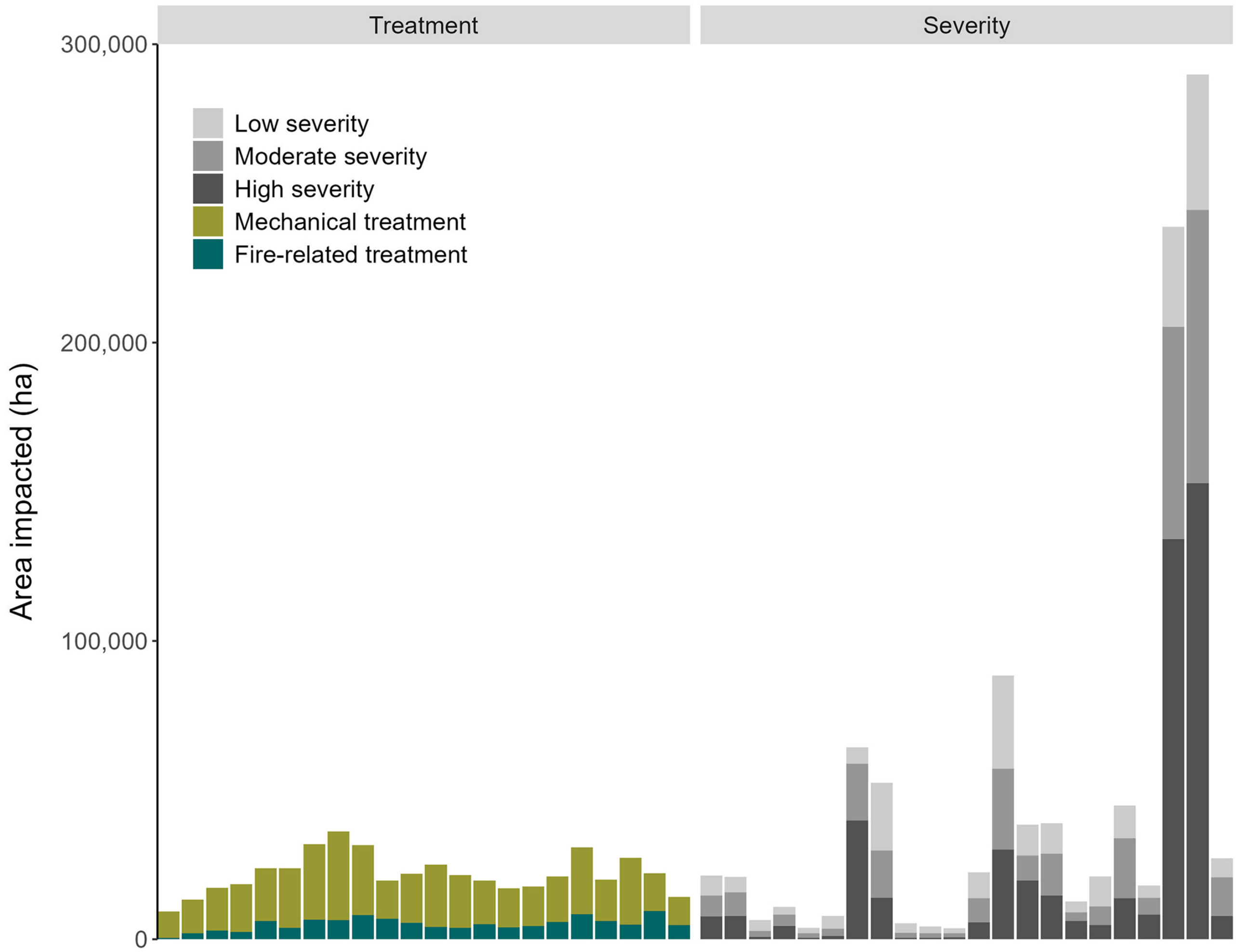

FIGURE 1 Annual treatment area by active management treatment type (left) and area burned by severity, excluding the "undetected change" category (right). Area is inclusive of all activity hectares annually, regardless of whether an individual area had a treatment in prior years.

largest fire years in 2020 and 2021. Over the entire study period, most of the area burned was on USFS lands (73%), likely due to the greater amount of YPMC area under their jurisdiction. A total of 475,137 ha burned at high severity in YPMC forests, which is 46% of all YPMC area burned. Annually, the lowest proportion of area burned at high severity was 9% in 2009, with the highest at 62% in 2007 (Figure 1). The percentage of area burned that was high severity by ownership was 47% for USFS, 22% for NPS, and 51% for private lands.

Roughly 567,166 ha burned with potentially beneficial wildfire (low to moderate severity; 54% of all burned YPMC area), slightly higher than the total area burned by high severity. The proportion of annual area burned in beneficial wildfire ranged from 38% (2007) to 91% (2009). The two largest fire years with the largest area of high severity in the Sierra Nevada YPMC, 2020 and 2021, still had substantial proportions of beneficial wildfire, 56% and 53% respectively (104,667 and 136,975 ha). Comparing the area burned by severity class and area treated, the mean annual treated area was 21,978 ha, and mean annual area burned was over twice that area (47,377 ha) of which 25,780 ha were beneficial fire (Figure 1). Annual area treated relative to annual area burned ranged from just 8% of area burned in the largest fire year in the YPMC (2021) to over six times more area than wildfire in 2005. Annual wildfire area exceeded treatment in 11 of the 22 years, with the annual area of potentially beneficial wildfire exceeding treatment in 8 of the 22 years. Over the entire study period, potentially beneficial wildfire affected 17% more YPMC forest area than all treatments combined, and four times more forest area than fire-related treatments alone. This relationship is also changing with increases in fire activity; from 2001 to 2011, beneficial wildfire impacted half (50%) of the area impacted by all treatments; in contrast, from 2012 to 2022, beneficial wildfire impacted nearly twice as much (187%) area. When compared to fire-related treatments

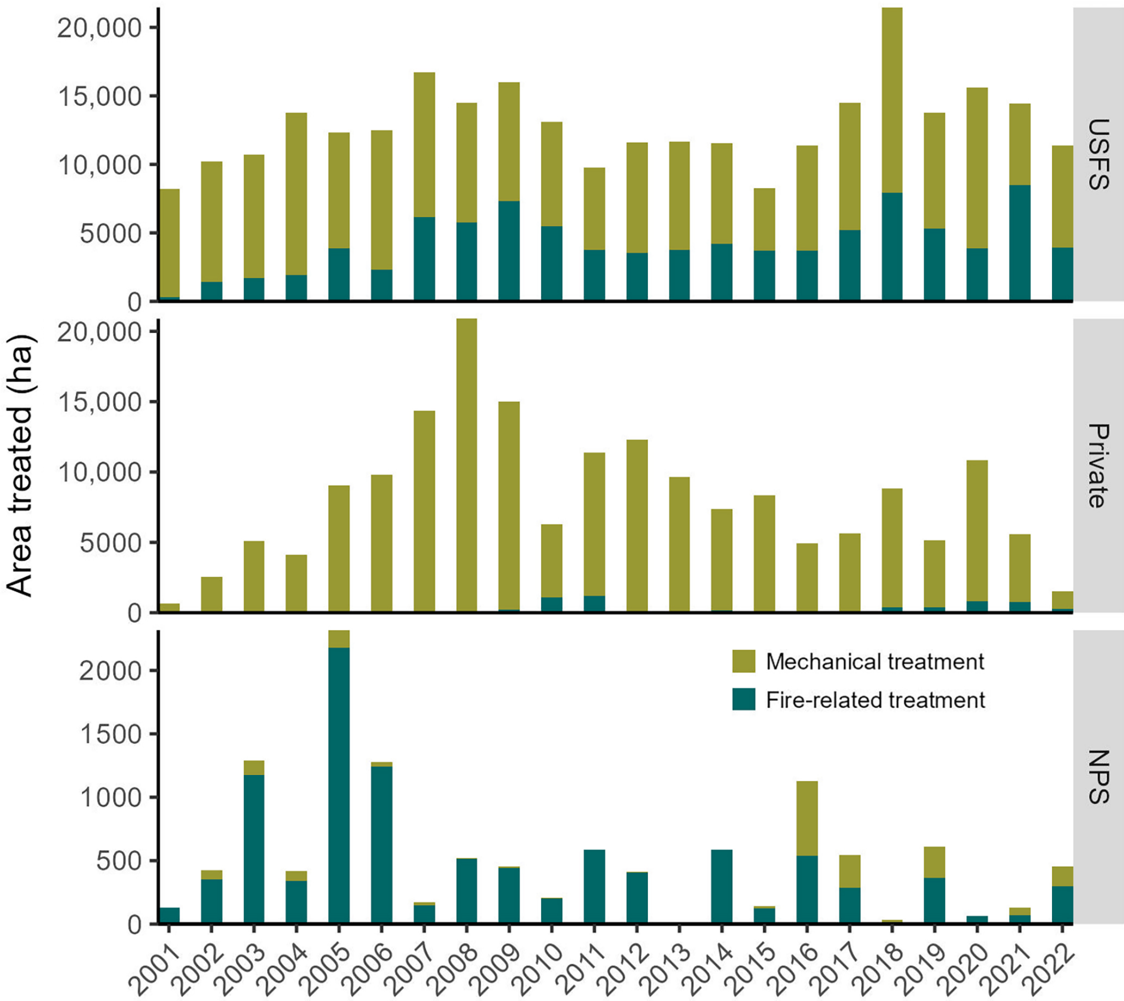

FIGURE 2 Trends in active management treatment type across the study period for the U.S. Forest Service (USFS), private landowners and National Park Service (NPS) from 2001 to 2022. Note the variation in the ranges of the *y*-axis. The total hectares of yellow pine/mixed conifer forest within each jurisdiction in 2001 is annotated in the upper left corner of each graph. Area is inclusive of all activity hectares, regardless of whether it was a second treatment in the same area or not.

alone, beneficial wildfire burned twice as much area in 2001–2011, increasing to over seven times as much area in the latter period.

Patterns of resistance to high-severity fire

Our resistance classifications for areas still forested in 2022 (No, Low, Moderate, or High resistance) showed good agreement with the ACCEL metric, probability of high-severity fire. Our classification assumes that the No resistance class would have the highest probability of high-severity fire, declining to lowest probability in the High resistance class. The mean probabilities of high-severity fire were 43% for No resistance, 33% for Low resistance, 21% for Moderate resistance, and 15% for High resistance.

Roughly 47% of the ~2.3 million ha that were classified as YPMC forest in 2001 have no resistance to severe wildfire as of the end of 2022 (Figure 3), with 32% classified as having some level of resistance (7% High resistance, 18% Moderate resistance and 8% Low resistance). Roughly 20% of the 2001 YPMC forest area was classified as Mature forest loss by 2022 due to high-severity fire. Of that, 202,800 ha are outside of the average dispersal range for Sierran conifers and are at risk of regeneration failure due to seed limitation. Nearly 20,000 ha have experienced short-interval high-severity reburns.

Patterns of resistance varied throughout the region. Of the 40 HUC8 watersheds in the study area, 22 had at least 10,000 ha of YPMC forest at the end of the study period. Within these, 16%–93% of each watershed had some level of resistance; five of those had <30%, a rough

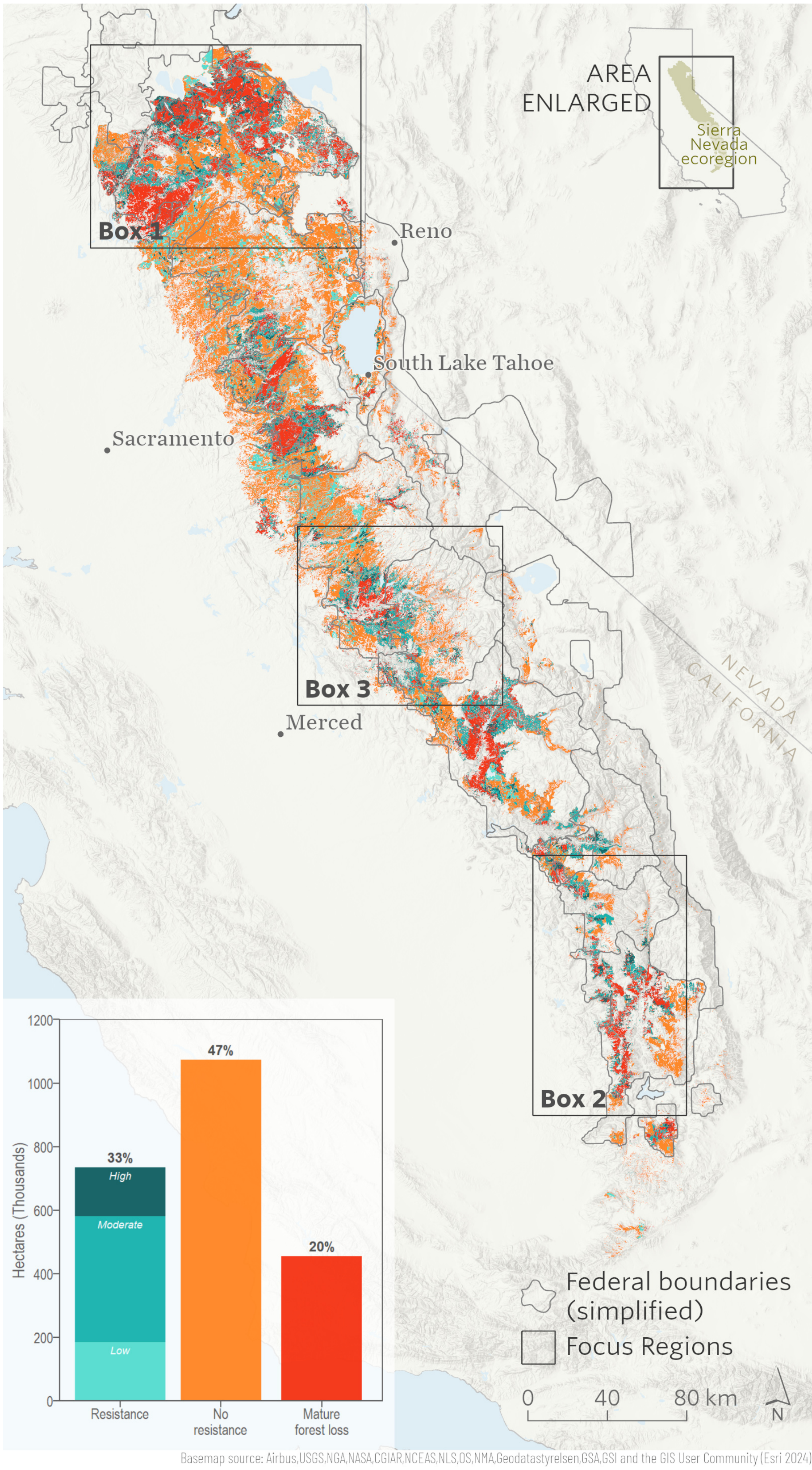

FIGURE 3 Map of the status of resistance for areas that were yellow pine and mixed conifer (YPMC) forest as of 2001. Note the regions that are highlighted in Boxes 1–3.

rule-of-thumb for minimum treatment area to reduce fire severity across landscapes. More broadly, the greatest total area of Mature forest loss occurred in the northern region, but these comprised a larger total relative area in the southern region. The central region has the largest concentration of areas with some level of resistance to high-severity fire (Figure 3).

Future treatment needs

Using the 22-year window for treatment longevity, our projections of retreatment needs over the next 22 years suggest that if maintaining existing resistance is the goal, there will be substantial re-treatment needs by 2044. If the current annual average treatment rate including all treatments continues, retreatment needs will not be met in 11 of the next 22 years, which in turn would mean no new first-entry treatments if maintenance needs were prioritized. Using the annual average for fire-related treatments only, maintenance needs would not be met in any year.

DISCUSSION

Trends in active management and wildfire

Despite significant state and federal investment in forest treatment (Charnley et al., 2023; State of California, 2022), we did not detect an increasing trend in area treated, with the average annual area treated covering just 0.01% of the YPMC forested area remaining as of 2022. Overall, mechanical treatments dominated the total treated area, with a peak in 2008. Steep declines after this period may be related to impacts from the 2008 financial crisis on the timber market (Keegan et al., 2012). Large fires in 2020 and 2021 likely also played a role, since wildfires can interrupt planned commercial operations. It can also increase the amount of salvage harvest in high-severity areas, which may reduce the treatments in green forests due to limitations in workforce availability and mill capacity (California Wildfire and Forest Resilience Task Force, 2022a). Other constraints that may be influencing the lack of increase in mechanical treatments include limited operating periods in critical habitat areas (U.S. Forest Service, 2006), as well as slope and access limitations.

Although fire-related treatments largely fluctuated throughout the study period, after initial increases in the early 2000s, there were substantial reductions in area treated in 2012–2016, which coincides with reductions in funding for fuel work provided under the 2000 National Fire Plan (Riddle, 2020). Reductions in fire-related treatments during this time may also have been influenced by the historic "hotter drought" (Stephenson et al., 2018), which likely made it difficult to find appropriate burn windows (Baijnath-Rodino et al., 2022; Swain et al., 2023). In addition, standing dead fuels from drought and beetle-killed trees (Young et al., 2017) in many areas of the central and southern Sierra may have added operational challenges. Large wildfire seasons like 2020 and 2021 can also limit the amount of burning because fire personnel are committed to wildfires elsewhere. Even when fire personnel are not committed to a wildfire, just the potential need for firefighters can limit implementation; for example, when fire danger was elevated in some regions of California, there was a temporary moratorium on burning on all USFS lands in 2024, even in areas with good conditions for prescribed fire, out of concern that fire personnel may be needed elsewhere (Venton, 2024). Escaped prescribed fires can also limit implementation of future burns due to risk aversion, which sometimes can be as extensive as the moratorium on burning on all USFS lands nationwide for much of 2022 (U.S. Forest Service, 2022c). The lack of an increasing trend in fire-related treatments is particularly troubling since they are the most critical for reducing fire severity (Davis et al., 2024; Fulé et al., 2012; Prichard et al., 2020; Safford et al., 2012; Shive et al., 2024; Taylor et al., 2022).

When considering differences in area treated by major landowners in the region (USFS, private and NPS), the NPS treated the smallest total footprint of YPMC area under their jurisdiction, yet there are important differences in the types of treatments conducted. On USFS and private lands, the fire-related treatments were predominantly pile burning, whereas the NPS treatments were primarily broadcast burning. In addition, the NPS manages much more wildfire for resource benefit than the USFS or private lands (van Wagtendonk et al., 2012), which has similar benefits to broadcast burning (Collins et al., 2016; Das et al., 2025). Managing these beneficial fires uses much of the same fuel personnel that would work on broadcast burns and pile burning, which is partly why the NPS appears to do so much less active treatment even relative to their YPMC area managed. Moreover, even though the percentage treated may be lower, the active treatments that are done are generally more important for fostering resistance to high-severity fire, given that fire-related reductions in woody fuels are linked with reduced fire severity (Brodie et al., 2024; Kalies & Yocom Kent, 2016). It would be interesting to track wildfires managed primarily for resource benefit separately, but a 2009 policy change that enabled all fires to be managed for a mix of resource benefit and suppression objectives (Fire Executive Council, 2009) has made them more difficult to track.

Similar to Knight et al. (2022), we observed a slight increase in fire-related treatments on private lands; looking more closely at the treatment types within our coarse mechanical treatments classification, there was also an increase in treatments focused primarily on fuels (e.g., mastication, chipping). These trends are likely related to substantial increases in funding available for private landowners to conduct active management (California Legislative Analysts Office, 2021; State of California, 2022; U.S. Forest Service, 2021, 2022b). The increase in fire-related treatments specifically may be linked to the rise of prescribed burn associations and cooperative burning, both of which empower private citizens to implement their own burns, with varying degrees of help from state and federal agencies (California Wildfire and Forest Resilience Task Force, 2022b). The increase in mechanical treatments on NPS lands reflects the agency's sense of urgency in reducing the potential for severe fire (National Park Service, 2022).

In contrast to the trends in treatment, we observed increasing total wildfire area burned and area burned with high-severity fire effects, which is consistent with other work in the Sierra Nevada that included more forest types (Miller, Safford, et al., 2009; Stevens et al., 2017; Williams et al., 2023). Roughly 45% of the YPMC area burned since 2001 was high severity. Although the largest area burned occurred on USFS lands, the largest area burned at high severity occurred on private lands (51%), which is similar to other work that found higher rates of severe fire in private industrial forest lands (Levine et al., 2022).

While these trends in high severity have been receiving the most research attention, due to the potential for forest loss (Davis et al., 2023; Shive et al., 2018) and other downstream impacts (Belongia et al., 2023), beneficial wildfire within the footprint of fires that are otherwise deemed catastrophic has received much less research attention. Several authors have noted that beneficial areas occur (Churchill et al., 2022; Larson et al., 2022; Meyer et al., 2021; Stevens et al., 2021), but our study quantifies the amount of low to moderate beneficial wildfire (54%) relative to high severity between 2001 and 2022. Our analysis also shows that beneficial wildfire is treating far more area than active management treatments, particularly in the last decade. Given the forecast for increasing fire activity, we suspect this trend is likely to continue (Bedsworth et al., 2018), suggesting that the overt inclusion of beneficial fire in future management plans is warranted.

Resistance classification

By combining the treatment and fire data, we evaluated landscape-scale changes in the YPMC, which: (1) provides a current snapshot of the "State of the Sierra Nevada" relative to altered fire regimes, highlighting the variation in current conditions across the range; and (2) when coupled with current treatment rates, highlights considerations for future management approaches.

The State of the Sierra Nevada

Wildfire has been the driving force of change across the region. Roughly 20% of the 2001 YPMC area was classified as Mature forest loss by 2022, with the most extensive concentration in the northern Sierra Nevada (see Box 1, Figure 4). Some of these areas will experience regeneration failures due to increased distances to seed source in large patches of high severity (Shive et al., 2018; Stevens et al., 2017), the warming climate (Davis et al., 2023; Stevens-Rumann et al., 2018), and the potential for high-severity reburns due to excess fuel loads (Coop et al., 2020). Nearly half of that area is out of the range of seed dispersal from lesser burned edges. Mature forest loss overlaps with critical habitat for mature forest specialist species, such as the California spotted owl (*Strix occidentalis occidentalis*), which is proposed for listing as threatened under the Endangered Species Act (U.S. Fish and Wildlife Service, 2023). This species requires mature forests for nesting, and while it hunts in small fire-created openings, it generally avoids large high-severity patches (Jones et al., 2016). These trends are particularly troubling for species with limited distributions, and in latitudes where the YPMC itself occurs in a narrower elevation band such as the southern Sierra Nevada (see Box 2, Figure 5).

The remaining YPMC area has retained mature forests, but 47% of it has no resistance and is at risk of experiencing high-severity fire. In these areas, increasing the pace and scale of management treatments and managed wildfire where possible could decrease this risk. However, 33% of the range has some level of resistance to high-severity fire, and most of that was classified as High or Moderate resistance, primarily due to beneficial wildfire. These areas are important because they maintain mature, live trees but generally have reduced surface fuels (Das et al., 2025). There is a large concentration of resistant forests in the central Sierra Nevada, likely due to past prescribed fires and managed wildfire (Collins et al., 2016; Kane et al., 2015; Lydersen et al., 2014), demonstrating how low-severity fire can beget low-severity fire (see Box 3, Figure 6).

BOX 1 Repeated megafires and rapid forest loss in the Northern Sierra Nevada

The majority of the yellow pine and mixed conifer (YPMC) forests in the northern Sierra Nevada burned at least once between 2001 and 2022 (Figure 4). Much of the area was burned in the 2021 Dixie Fire, the largest fire on record in California, which burned through both long-unburned forests and many recent wildfire areas. This region is most strongly dominated by large contiguous areas of Mature forest loss, including the greatest concentration of short-interval, high-severity reburns (not shown). These reburns are driven by a combination of topography and the stature of the regenerating vegetation (Steel et al., 2021), leaving the region at elevated risk for extensive, persistent type conversions (Coop et al., 2020).

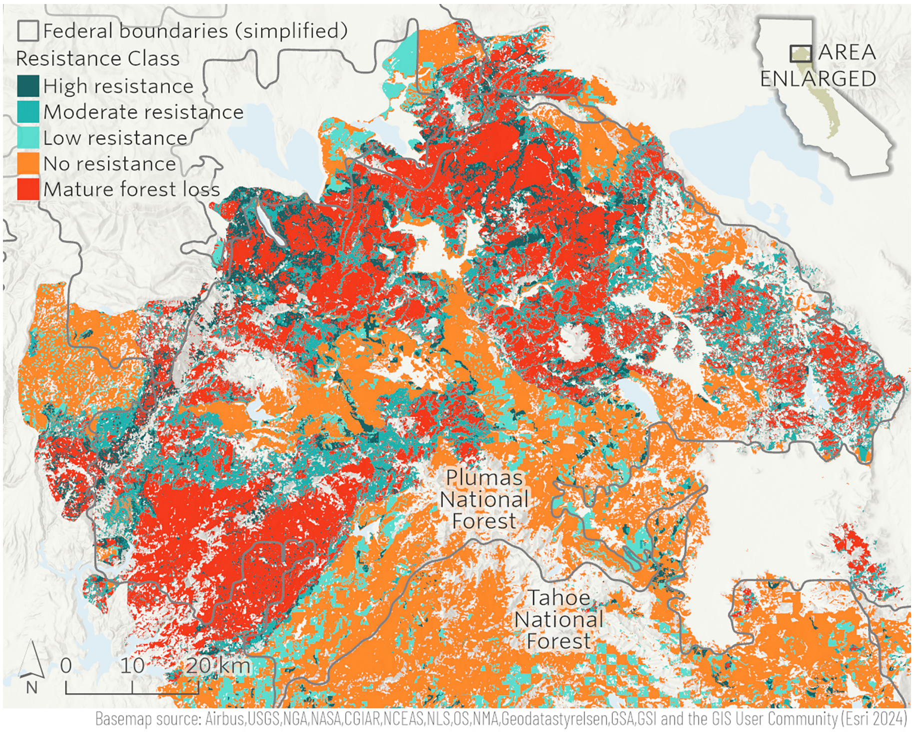

FIGURE 4 Detail of the area of the yellow pine and mixed conifer (YPMC) forests in the northern Sierra Nevada that burned at least once between 2001 and 2022. See Box 1 for full explanation.

When including beneficial fire, the target of treating at least ~30% of the landscape to reduce landscape-level fire severity (Ott et al., 2023) has been met at the range-wide scale. However, since this is driven by wildfire, it is spatially aggregated, resulting in an even level of resistance across the range (Figure 3). When considered on a watershed scale (HUC8), the YPMC in some watersheds is dominated by having some level of resistance across their 2022 YPMC forested area, but nearly half do not meet the 30% threshold. While these high-level analyses are not intended for stand-scale management decision making, they highlight how the variation in disturbance history across the range has resulted in very different ecological consequences, suggesting distinct potential future pathways and considerations for future management (Boxes 1–3).

Considering retreatment needs

Our resistance classification highlights the variation in opportunities to initiate, enhance, and maintain resistance in YPMC forested areas across the landscape. In areas of No resistance, a first-entry treatment would initiate the process of creating resistance, with the use of a mechanical thinning or prescribed fire, creating Low or Moderate resistance, respectively. In areas that already have some level of resistance, follow-up treatments will be required to enhance and maintain highly resistant forests. A fire-related treatment is needed to enhance resistance in Low resistance areas as soon as possible, given the limitations in thinning-only treatments at reducing fire severity (Brodie et al., 2024; Davis et al., 2024; Shive et al., 2024). In Moderate resistance areas (low to moderate severity), another fire-related treatment or mechanical thinning is needed to move the stand into High resistance. This is because, although most fine woody surface fuels will have been consumed (Das et al., 2025), mimicking the effects of a prescribed fire, the fire-killed trees will eventually fall to the forest floor, resulting in high surface fuel loads (Collins et al., 2018). Managers could wait until this occurs to conduct a prescribed fire, or they could thin out the dead biomass, effectively reversing the traditional order of treatments (thin then burn), but resulting in a similar outcome. In very low-severity fire areas, persistent live tree density may still exceed target conditions for drought and fire resistance, which could be further thinned mechanically. Critically, High resistance areas will also need another treatment to *maintain* resistance, although on a lengthier time frame.

Forecasting into the future, at current annual treatment rates we would not be able to maintain the current resistance areas in half of the next 22 years, nor any year if we consider fire-related treatments alone, let alone moving into additional No resistance areas. This is also a highly conservative estimate, since our treatment longevity window is likely an overestimate, applying to the High resistance areas at best (a recent study suggests treatments last ~10 years; Davis et al., 2024). With a 10-year window, retreatment needs would substantially increase in the near future, particularly considering that the Low and Moderate resistance areas will likely need additional treatments even sooner. While we recognize that not all of the areas that currently have some level of resistance will be high priorities for maintenance treatments, this thought exercise highlights the critical need to consider retreatment as forest managers prioritize treatments. Prioritization efforts are generally driven by a range of considerations, including values at risk, ecosystem services (Manley et al., 2023), future climate suitability, and implementation feasibility. Our range-wide analysis highlights an additional consideration for long-term planning—the potentially competing needs for first-entry treatments in long unburned forests, treatments that enhance Low to Moderate resistance, and treatments that maintain High resistance.

One way to address these needs is continuing to increase the pace and scale of treatments, which would require sustained funding, an adequate workforce, and streamlining compliance (California Forest Management Task Force, 2021; Schultz et al., 2019). Embracing managed wildfire is another pathway to increasing resistance across the landscape (North et al., 2012, 2024), which has

BOX 2 Severe fire threats to sensitive species in the southern Sierra Nevada

The yellow pine and mixed conifer (YPMC) is limited to a narrow elevation band in the southern Sierra Nevada, which includes extensive areas of Mature forest loss, mostly from 2020 and 2021 wildfires (Figure 5). This estimate is conservative, as it does not include the extensive drought and beetle impacts to this region captured by Steel et al. (2023).

Fires have impacted two important species with limited distribution in the region: the Pacific fisher and the giant sequoia (*Sequoiadendron giganteum* (Lindl.) J. Buchholz). Pacific fishers are house cat-size meso-carnivores that depend on mature forests with complex understories for foraging and denning. The southern Sierra Nevada population is endangered, with wildfire-driven habitat loss listed as one of the greatest threats to their persistence (U.S. Fish and Wildlife Service, 2020). Recent fires have reduced fisher habitat and likely have had a significant impact on habitat connectivity (Thompson et al., 2021).

The iconic giant sequoia are some of the oldest and largest trees on earth, most of which occur in this region. Although they are highly fire adapted, recent increases in fire severity are well outside of their historical range of variability (Stephenson, 1999; Swetnam, 1993). In 2020 and 2021, an estimated 13%–19% of all large giant sequoias were killed by wildfire (Shive et al., 2021; Stephenson & Brigham, 2021). In some areas, fires were so severe that regeneration may be inadequate (Soderberg et al., 2024); a surprise for this semi-serotinous species (Hartesveldt et al., 1969). However, most of the area burned in giant sequoia groves was less severe where mature sequoia survived, creating significant conservation opportunities. Maintaining the mature forests that survived recent wildfires could be an important avenue for ensuring the persistence of both of these species.

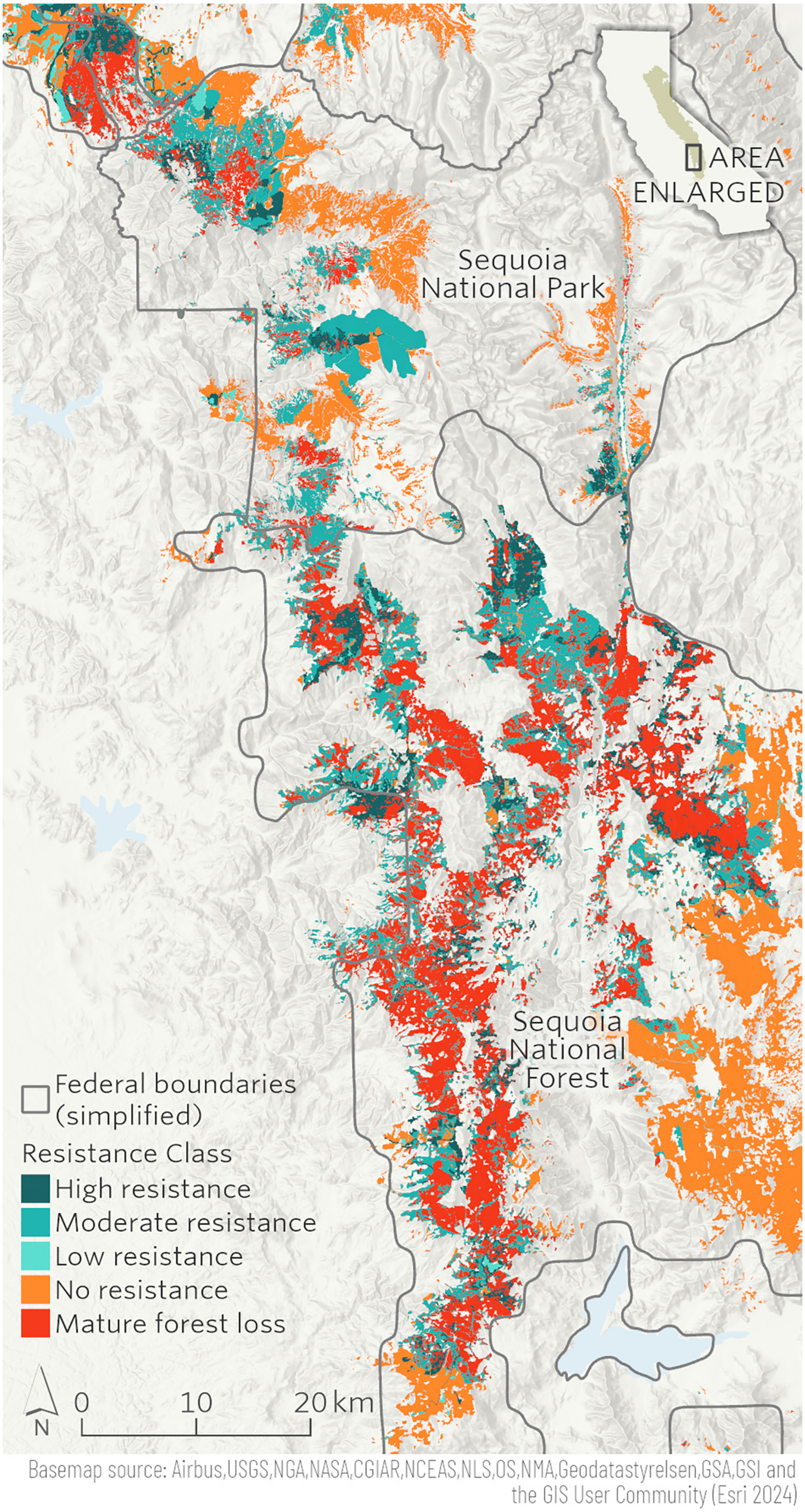

FIGURE 5 Detail of the yellow pine and mixed conifer (YPMC) forest in the southern Sierra Nevada, which includes extensive areas of Mature forest loss, mostly from 2020 and 2021 wildfire. See Box 2 for full explanation.

had considerable research attention (Collins et al., 2016). Yet there is another relatively underused "tool" in the toolbox: capitalizing on recently burned areas.

Recent fires have the potential to increase the pace and scale of fire-related treatments. Where recent wildfires have reduced surface fuels, they can facilitate prescribed fire or a wildfire for resource benefit by functioning as a fuel break (Collins et al., 2007; Parks et al., 2015). Prescribed burns could be used to burn out unburned pockets within a fire perimeter or on adjacent unburned lands, using the wildfire as anchor. This can reduce operational complexity and the risk of escape, allowing fire managers to "burn into the black." This approach has the potential to expand the area treated by prescribed fire, but it would require agencies to be nimble. Environmental compliance and burn planning can take several years (Schultz et al., 2012, 2019), which suggests that agencies would likely need to identify these

BOX 3 Silver linings in the central Sierra Nevada

By 2022, the central Sierra Nevada had the largest relative area with some level of resistance, particularly in the Moderate and High resistance classes (Figure 6). Inside Yosemite National Park (YNP), this is due to prescribed fire and wildfires managed for resource benefit since 1972 (van Wagtendonk et al., 2012). After nearly 50 years of managed wildfire, the area is predominantly characterized by High to Moderate resistance and small patches of Mature forest loss and short-interval high-severity reburns, which have restored fine-scale habitat heterogeneity at the landscape scale (Boisramé et al., 2017; Stephens et al., 2021).

In recent decades, YNP has expanded its use of managed wildfire to most of the park, and has continued to conduct prescribed fires. These management activities have helped reduce subsequent wildfire severity and facilitated the ability of firefighters to engage wildfires (Hankin et al., 2023; Lydersen et al., 2014; Marcum, 2013). YNP is 95% designated wilderness, which likely makes managing wildfires for resource benefit easier than in areas with other management goals or in mixed ownership. Managed wildfire has also been used as a restoration tool in the Stanislaus National Forest to a more limited extent (Fites-Kaufman et al., 2013).

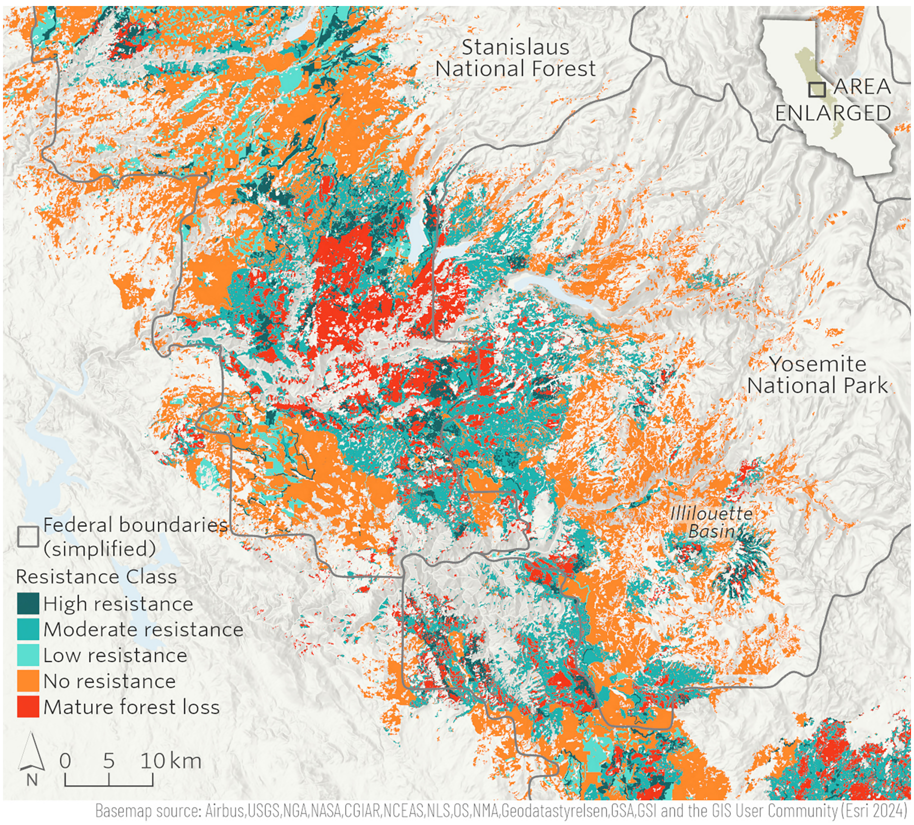

FIGURE 6 Detail of the central Sierra Nevada, which had the largest relative area with some level of resistance. See Box 3 for full explanation.

opportunities quickly after the fire, so that they can initiate and complete the necessary planning and compliance and then implement treatments, before fuels re-accumulate (Collins et al., 2016; Das et al., 2025). Policies that make prescribed fire easier to implement could support agencies' ability to respond quickly to these opportunities (Clark et al., 2022, 2024; Schultz et al., 2019).

Working with wildfires could also amplify the *impact* of an individual treatment by capitalizing on the "free" treatment from the wildfire. Moderate resistance (e.g., prescribed fire or low- to moderate-severity wildfire) generally needs an additional treatment to enhance resistance. If managers have the capacity to thin 100 ha, thinning 100 ha of Moderate resistance has the potential to move that stand into a High resistance condition, whereas if they used those resources to instead conduct a first entry in a long-unburned forest, that forest will still need an additional prescribed fire treatment to become highly resistant to high-severity fire. In this case, the effort and cost of the treatment could have a greater net benefit if it was done within the wildfire footprint than it would have as a first-entry treatment (e.g., more "bang for the buck"). This approach has been proposed in several postfire frameworks (Meyer et al., 2021; Stevens et al., 2021) but to date has not yet been widely embraced. However, early adopters include the Plumas National Forest (2023, 2024), and in the Giant Sequoia National Monument, where managers are conducting thinning and pile burning treatments in lower severity burned giant sequoia groves and adjoining mixed conifer forests (Sequoia National Forest and Giant Sequoia National Monument, 2023a, 2023b).

The decision to leverage these recently burned areas will intersect with other important factors that drive management priorities. For example, managers may choose to do a first-entry treatment in an unburned old-growth stand that serves as critical owl habitat, versus enhancing resistance in an area of young second-growth mixed conifer forest that is forecasted to become inhospitable for the dominant species. However, where priority areas align with recently burned, beneficial wildfire, there could be significant opportunities to increase the pace, scale, and impact of forest treatments.

Finally, we note that this approach still relies on active treatment, which will be subject to the same challenges and constraints that have been known for some time (Miller et al., 2020; Quinn-Davidson et al., 2011; Schultz et al., 2019; Stephens & Ruth, 2005; USDA and USDI, 1995). This suggests that significant forested areas may not be treated or will not have had enough treatment (e.g., the follow-up fire-related treatment after a thinning treatment) before being exposed to an unplanned wildfire. Landscape-scale planning frameworks such as the Resist, Accept, Direct (RAD) framework (Schuurman et al., 2022) that explicitly identify areas where fire or drought-driven ecosystem transformation would be acceptable or even desirable (Kreider et al., 2024) can help managers identify where they want to invest in resisting change over the long term. RAD and other related approaches have been proposed for postfire management planning (Meyer et al., 2021; Stevens et al., 2021), but these approaches could also be used to support treatment prioritization at landscape scales, integrating both pre- and post-disturbance areas.

Study limitations

There are several limitations to our analysis. First, our remote sensing-based maps of forest types and treatment databases each have their own imperfections (Knight et al., 2022; Ohlmann & Gregory, 2002), so their intersection may contribute to some error in our assessment of treatment rates. In addition, we were unable to include work performed under the State of California's Nonindustrial Timber Management Plans and Exemptions (CAL FIRE, 2024), because they are difficult to track spatially. However, by definition, treatments performed under these avenues generally impact less land and are often less intensive. Despite these limitations, we believe that at the scale of the YPMC across the Sierra Nevada, the overall trends are accurate, particularly the core result: that wildfire has been treating more area than active management, particularly over the last decade.

In addition, we did not consider the potential benefits of smaller patches of high-severity fire (e.g., <100 ha; Collins & Stephens, 2010) that provide important habitat for early seral species (Stillman et al., 2019) and create habitat heterogeneity and pyrodiversity at landscape scales (Boisramé et al., 2017; Steel et al., 2024). However, our quantification of the area outside the zone of conifer tree seed dispersal (202,800 ha, ~44% of the total high-severity area) likely reflects most of the area covered by larger, undesirable patches. An additional spatial analysis of patch shape and complexity would be needed to understand the degree to which the remaining high-severity area is contributing to a heterogeneous landscape.

To create a broad overview of the variation in conditions at the range-wide scale, we made several assumptions in our resistance classification that gloss over important nuance in local conditions. First, we did not consider how differing time since treatment/fire impacts the current state of resistance to high-severity fire. For simplicity's sake, a low-severity fire in 2001 and in 2022 were treated the same, for example, but of course fuel accumulation from the 2001 fire will mean that at present, conditions there will be much less resistant than those created in the more recent fire. Using fuel accumulation rates, or even just an even annual decline in resistance, could help highlight these differences. However, at the range-wide scale, this was not visible and did not add much in conveying our main points, and our intent was a broad overview of the region. Lastly, we did not consider other important forest health issues, some of which will likely interact to influence future fire resilience. For example, the extensive drought and beetle mortality that occurred throughout the southern Sierra Nevada is resulting in large pulses of additional fuels, which can elevate the potential for mass fire (Stephens et al., 2022). However, in the case of increased fuel loading due to drought mortality, it is primarily impacting long unburned forests, which are classified as having No resistance anyway.

CONCLUSIONS

Although it is unsurprising that beneficial fire is treating more area than active treatment, our study quantified the degree to which these differ. By mapping resistance across the range, we highlight areas where managers could capitalize on these otherwise "undesirable" wildfires. Recently burned areas offer a range of opportunities to increase the pace, scale, and *impact* of forest management treatments.

Yet to capitalize on these opportunities, forest managers will likely need additional support. While the area at risk of type conversion due to seed limitation presents an enormous challenge for managers, there are many studies on the patterns of postfire regeneration failures (Chambers et al., 2016; Davis et al., 2023; Kemp et al., 2016; Shive et al., 2018; Stevens et al., 2017; Stevens-Rumann & Morgan, 2019) and planting success (Collins & Roller, 2013; Ouzts et al., 2015; Sorenson et al., 2025), as well as tools to support reforestation planning (Shive et al., 2018; Stewart et al., 2021), including some that consider climate (Stewart et al., 2024). In contrast, the roughly one-third of the forested area with some resistance due to wildfire, where there are opportunities to enhance or maintain resistance, has received far less research attention. Future work to better characterize postfire fuels and future fuel accumulation could help inform management in recently burned areas. Our work highlights not only the opportunities created by wildfires, but how they interact with treatments to impact resistance at landscape scales. This exercise can help forest managers better understand current capacity and landscape conditions and put them in the context of future maintenance needs, facilitating more informed plans for the future.

ACKNOWLEDGMENTS

Thank you to Margaret Farley and Mark Tukman from Tukman Geospatial LLC for their contribution to the spatial analysis of forest resistance. Thank you to Daniel Foster for coding help and to Michelle Coppoletta for productive discussions around the analyses. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US government.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data and workflow (Shive et al., 2025) are available from Dryad: https://doi.org/10.5061/dryad.ttdz08m7d.

ORCID

Kristen L. Shive https://orcid.org/0000-0002-5633-2528
Clarke A. Knight https://orcid.org/0000-0003-0002-6959
Kristen N. Wilson https://orcid.org/0000-0003-4769-2086

REFERENCES

Abatzoglou, J. T., and A. P. Williams. 2016. "Impact of Anthropogenic Climate Change on Wildfire across Western US Forests." *Proceedings of the National Academy of Sciences of the United States of America* 113: 11770–75. https://doi.org/10.1073/pnas.1607171113.

Baijnath-Rodino, J. A., S. Li, A. Martinez, M. Kumar, L. N. Quinn-Davidson, R. A. York, and T. Banerjee. 2022. "Historical Seasonal Changes in Prescribed Burn Windows in California." *Science of the Total Environment* 836: 155723. https://doi.org/10.1016/j.scitotenv.2022.155723.

Bedsworth, L., D. Cayan, G. Franco, L. Fisher, and S. Ziaja. 2018. "Statewide Summary Report. California's Fourth Climate Change Assessment (No. SUMCCCA4-2018–013)." https://www.energy.ca.gov/sites/default/files/2019-11/Statewide_Reports-SUM-CCCA4-2018-013_Statewide_Summary_Report_ADA.pdf.

Belongia, M. F., C. Hammond Wagner, K. Q. Seipp, and N. K. Ajami. 2023. "Building Water Resilience in the Face of Cascading Wildfire Risks." *Science Advances* 9: eadf9534. https://doi.org/10.1126/sciadv.adf9534.

Boisramé, G. F. S., S. E. Thompson, M. Kelly, J. Cavalli, K. M. Wilkin, and S. L. Stephens. 2017. "Vegetation Change during 40 Years of Repeated Managed Wildfires in the Sierra Nevada, California." *Forest Ecology and Management* 402: 241–252. https://doi.org/10.1016/j.foreco.2017.07.034.

Brodie, E. G., E. E. Knapp, W. R. Brooks, S. A. Drury, and M. W. Ritchie. 2024. "Forest Thinning and Prescribed Burning Treatments Reduce Wildfire Severity and Buffer the Impacts of Severe Fire Weather." *Fire Ecology* 20: 17. https://doi.org/10.1186/s42408-023-00241-z.

CAL FIRE. 2023a. "Timber Harvesting." CAL FIRE (California Department of Forestry and Fire Protection).

CAL FIRE. 2023b. "Historical Timber." CAL FIRE (California Department of Forestry and Fire Protection).

CAL FIRE. 2023c. "Historic Fire Perimeters 2022 Geodatabase: Prescribed Fire Layer (rxburn22_1)." https://www.fire.ca.gov/what-we-do/fire-resource-assessment-program/fire-perimeters.

CAL FIRE. 2024. *Forest Practice Rules 2024 (No. Title 14, California Code of Regulations Chapters 4, 4.5 and 10)*. Sacramento, CA: California Department of Forestry and Fire Protection Resource Management, Forest Practice Program. https://bof.fire.ca.gov/media/qs5p1yk4/2024-forest-practice-rules-and-act-final.pdf.

California Forest Management Task Force. 2021. "California's Wildfire and Forest Resilience Action Plan: A Comprehensive Strategy of the Governor's Forest Management Task Force." https://wildfiretaskforce.org/wp-content/uploads/2022/12/californiawildfireandforestresilienceactionplan.pdf.

California Legislative Analysts Office. 2021. "Wildfire and Forest Resilience Early Action Package." https://lao.ca.gov/Publications/Report/4414.

California Wildfire & Forest Resilience Task Force. 2023. "California Wildfire and Landscape Resilience Interagency Treatment Tracking System Database. 2001–2022." Obtained Directly from Agency.

California Wildfire and Forest Resilience Task Force. 2022a. "Roadmap to a Million Acres. State of California."

California Wildfire and Forest Resilience Task Force. 2022b. "California's Strategic Plan for Expanding the Use of Beneficial Fire. State of California." https://wildfiretaskforce.org/wp-content/uploads/2022/05/californias-strategic-plan-for-expanding-the-use-of-beneficial-fire.pdf.

California Wildfire and Forest Resilience Task Force. 2024. "Fire Hand Crews." https://wildfiretaskforce.org/fire-crews/.

Chambers, M. E., P. J. Fornwalt, S. L. Malone, and M. A. Battaglia. 2016. "Patterns of Conifer Regeneration Following High Severity Wildfire in Ponderosa Pine – Dominated Forests of the Colorado Front Range." *Forest Ecology and Management* 378: 57–67. https://doi.org/10.1016/j.foreco.2016.07.001.

Charnley, S., E. J. Davis, and J. Schelhas. 2023. "The Bipartisan Infrastructure Law and the Forest Service: Insights for Local Job Creation and Equity from the American Recovery and Reinvestment Act." *Journal of Forestry* 121(3): 282–291. https://doi.org/10.1093/jofore/fvad009.

Churchill, D. J., S. M. A. Jeronimo, P. F. Hessburg, C. A. Cansler, N. A. Povak, V. R. Kane, J. A. Lutz, and A. J. Larson. 2022. "Post-Fire Landscape Evaluations in Eastern Washington, USA: Assessing the Work of Contemporary Wildfires." *Forest Ecology and Management* 504: 119796. https://doi.org/10.1016/j.foreco.2021.119796.

Clark, S. A., J. N. Archer, S. L. Stephens, B. M. Collins, and D. L. Hankins. 2024. "Realignment of Federal Environmental Policies to Recognize Fire's Role." *Fire Ecology* 20(1): 74. https://doi.org/10.1186/s42408-024-00301-y.

Clark, S. A., A. Miller, and D. L. Hankins. 2022. *Current Barriers to the Expansion of Cultural Burning and Prescribed Fire in California and Recommended Solutions*. Happy Camp, CA: Karuk Tribe. https://karuktribeclimatechangeprojects.files.wordpress.com/2022/06/karuk-prescribed-fire-rpt_2022_v2-1.pdf.

Collins, B. M., M. Kelly, J. W. van Wagtendonk, and S. L. Stephens. 2007. "Spatial Patterns of Large Natural Fires in Sierra Nevada Wilderness Areas." *Landscape Ecology* 22: 545–557. https://doi.org/10.1007/s10980-006-9047-5.

Collins, B. M., J. M. Lydersen, R. G. Everett, and S. L. Stephens. 2018. "How Does Forest Recovery Following Moderate-Severity Fire Influence Effects of Subsequent Wildfire in Mixed-Conifer Forests?" *Fire Ecology* 14: 3. https://doi.org/10.1186/s42408-018-0004-x.

Collins, B. M., J. M. Lydersen, D. L. Fry, K. Wilkin, T. Moody, and S. L. Stephens. 2016. "Variability in Vegetation and Surface Fuels across Mixed-Conifer-Dominated Landscapes with over 40 Years of Natural Fire." *Forest Ecology and Management* 381: 74–83. https://doi.org/10.1016/j.foreco.2016.09.010.

Collins, B. M., J. D. Miller, A. E. Thode, M. Kelly, J. W. van Wagtendonk, and S. L. Stephens. 2009. "Interactions among Wildland Fires in a Long-Established Sierra Nevada Natural Fire Area." *Ecosystems* 12: 114–128. https://doi.org/10.1007/s10021-008-9211-7.

Collins, B. M., and G. B. Roller. 2013. "Early Forest Dynamics in Stand-Replacing Fire Patches in the Northern Sierra Nevada, California, USA." *Landscape Ecology* 28: 1801–13. https://doi.org/10.1007/s10980-013-9923-8.

Collins, B. M., and S. L. Stephens. 2010. "Stand-Replacing Patches within a 'Mixed Severity' Fire Regime: Quantitative Characterization Using Recent Fires in a Long-Established Natural Fire Area." *Landscape Ecology* 25: 927–939. https://doi.org/10.1007/s10980-010-9470-5.

Coop, J. D., S. A. Parks, C. S. Stevens-Rumann, S. D. Crausbay, P. E. Higuera, M. D. Hurteau, A. Tepley, et al. 2020. "Wildfire-Driven Forest Conversion in Western North American Landscapes." *BioScience* 70: 659–673. https://doi.org/10.1093/biosci/biaa061.

Das, A. J., L. M. Rosenthal, and K. L. Shive. 2025. "The Effectiveness of Wildfire at Meeting Restoration Goals across a Fire Severity Gradient in the Sierra Nevada." *Forest Ecology and Management* 580: 122486. https://doi.org/10.1016/j.foreco.2024.122486.

Davis, K. T., J. Peeler, J. Fargione, R. D. Haugo, K. L. Metlen, M. D. Robles, and T. Woolley. 2024. "Tamm Review: A Meta-Analysis of Thinning, Prescribed Fire, and Wildfire Effects on Subsequent Wildfire Severity in Conifer Dominated Forests of the Western US." *Forest Ecology and Management* 561: 121885. https://doi.org/10.1016/j.foreco.2024.121885.

Davis, K. T., M. D. Robles, K. B. Kemp, P. E. Higuera, T. Chapman, K. L. Metlen, J. L. Peeler, et al. 2023. "Reduced Fire Severity Offers Near-Term Buffer to Climate-Driven Declines in Conifer Resilience across the Western United States." *Proceedings of the National Academy of Sciences of the United States of America* 120: e2208120120. https://doi.org/10.1073/pnas.2208120120.

Esri. 2024. "ArcGIS Pro: Release 3.3." https://pro.arcgis.com/en/pro-app/3.3/get-started/release-notes.htm.

Fettig, C. J., J. B. Runyon, C. S. Homicz, P. M. A. James, and M. D. Ulyshen. 2022. "Fire and Insect Interactions in North American Forests." *Current Forestry Reports* 8: 301–316. https://doi.org/10.1007/s40725-022-00170-1.

Fire Executive Council. 2009. *Guidance for Implementation of Federal Wildland Fire Management Policy*. Washington, DC: U.S. Department of Agriculture/U.S. Department of Interior. https://www.doi.gov/sites/default/files/uploads/2009-wfm-guidance-for-implementation.pdf.

Fites-Kaufman, J. A., E. Noonan, and D. Ramirez. 2013. *Evaluation of Wildland Fire Use Fires on the Sequoia and Stanislaus National Forests in 2003: Effects in Relation to Historic Regimes and Resource Benefits*. Sonora, CA: USDA Forest Service Enterprise Program. https://www.frames.gov/catalog/65741.

Fulé, P. Z., J. E. Crouse, J. P. Roccaforte, and E. L. Kalies. 2012. "Do Thinning and/or Burning Treatments in Western USA Ponderosa or Jeffrey Pine-Dominated Forests Help Restore Natural Fire Behavior?" *Forest Ecology and Management* 269: 68–81. https://doi.org/10.1016/j.foreco.2011.12.025.

GreenInfo Network. 2022. "California Protected Areas Database (CPAD)." https://calands.org/.

Hagmann, R. K., P. F. Hessburg, S. J. Prichard, N. A. Povak, P. M. Brown, P. Z. Fulé, R. E. Keane, et al. 2021. "Evidence for Widespread Changes in the Structure, Composition, and Fire Regimes of Western North American Forests." *Ecological Applications* 31: e02431. https://doi.org/10.1002/eap.2431.

Hankin, L. E., C. T. Anderson, G. J. Dickman, P. Bevington, and S. L. Stephens. 2023. "How Forest Management Changed the Course of the Washburn Fire and the Fate of Yosemite's Giant Sequoias (*Sequoiadendron giganteum*)." *Fire Ecology* 19: 40. https://doi.org/10.1186/s42408-023-00202-6.

Hartesveldt, R. J., H. T. Harvey, H. S. Shellhammer, and R. E. Stecker. 1969. "Sequoias' Dependence on Fire." *Science* 166: 552–53. https://doi.org/10.1126/science.166.3905.552.b.

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. https://doi.org/10.1016/j.foreco.2019.01.033.

Jones, G. M., R. Gutiérrez, D. J. Tempel, S. A. Whitmore, W. J. Berigan, and M. Z. Peery. 2016. "Megafires: An Emerging Threat to Old-Forest Species." *Frontiers in Ecology and the Environment* 14: 300–306. https://doi.org/10.1002/fee.1298.

Kalies, E. L., and L. L. Yocom Kent. 2016. "Tamm Review: Are Fuel Treatments Effective at Achieving Ecological and Social Objectives? A Systematic Review." *Forest Ecology and Management* 375: 84–95. https://doi.org/10.1016/j.foreco.2016.05.021.

Kane, V. R., C. A. Cansler, N. A. Povak, J. T. Kane, R. J. McGaughey, J. A. Lutz, D. J. Churchill, and M. P. North. 2015. "Mixed Severity Fire Effects within the Rim Fire: Relative Importance of Local Climate, Fire Weather, Topography, and Forest Structure." *Forest Ecology and Management* 358: 62–79. https://doi.org/10.1016/j.foreco.2015.09.001.

Keegan, C. E., C. B. Sorenson, T. A. Morgan, J. M. Daniels, and S. W. Hayes. 2012. *Impact of the Great Recession Onm the Forest Products in Teh Western United States, in: Moving from Status to Trends: Forest Inventory and Analysis (FIA) Symposium 2012, General Technical Report* 5–9. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. https://www.fs.usda.gov/nrs/pubs/gtr/gtr_nrs-p-105.pdf.

Kemp, K. B., P. E. Higuera, and P. Morgan. 2016. "Fire Legacies Impact Conifer Regeneration across Environmental Gradients in the U.S. Northern Rockies." *Landscape Ecology* 31: 619–636. https://doi.org/10.1007/s10980-015-0268-3.

Knight, C. A., R. E. Tompkins, J. A. Wang, R. York, M. L. Goulden, and J. J. Battles. 2022. "Accurate Tracking of Forest Activity Key to Multi-Jurisdictional Management Goals: A Case Study in California." *Journal of Environmental Management* 302: 114083. https://doi.org/10.1016/j.jenvman.2021.114083.

Kreider, M. R., P. E. Higuera, S. A. Parks, W. L. Rice, N. White, and A. J. Larson. 2024. "Fire Suppression Makes Wildfires more Severe and Accentuates Impacts of Climate Change and Fuel Accumulation." *Nature Communications* 15: 2412. https://doi.org/10.1038/s41467-024-46702-0.

Larson, A. J., S. M. A. 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. https://doi.org/10.1016/j.foreco.2021.119680.

Levine, J. I., B. M. Collins, Z. L. Steel, P. de Valpine, and S. L. Stephens. 2022. "Higher Incidence of High-Severity Fire in and near Industrially Managed Forests." *Frontiers in Ecology and the Environment* 20: 397–404. https://doi.org/10.1002/fee.2499.

Lydersen, J. M., M. P. North, and B. M. Collins. 2014. "Severity of an Uncharacteristically Large Wildfire, the Rim Fire, in Forests with Relatively Restored Frequent Fire Regimes." *Forest Ecology and Management* 328: 326–334. https://doi.org/10.1016/j.foreco.2014.06.005.

Manley, P. N., N. A. Povak, K. N. Wilson, M. L. Fairweather, V. Griffey, and L. L. Long. 2023. *Blueprint for Resilience: The Tahoe-Central Sierra Initiative (No. PSW-GTR-277)*. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. https://doi.org/10.2737/PSW-GTR-277.

Marcum, D. 2013. "Risky Measures to Save Big Trees from Rim Fire Worked." *The LA Times*. https://www.latimes.com/local/la-xpm-2013-sep-22-la-me-rim-fire-giant-sequoias-20130923-story.html.

McDonald, P. M. 1980. *Seed Dissemination in Small Clearcuttings in North-Central California*. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. https://research.fs.usda.gov/treesearch/28954.

Meyer, M. D., J. W. Long, and H. D. Safford, eds. 2021. *Postfire Restoration Framework for National Forests in California* (Gen. Tech. Rep. No. PSW-GTR-270). Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station.

Miller, J. D., E. E. Knapp, C. H. Key, C. N. Skinner, C. J. Isbell, R. M. Creasy, and J. W. Sherlock. 2009. "Calibration and Validation of the Relative Differenced Normalized Burn Ratio (RdNBR) to Three Measures of Fire Severity in the Sierra Nevada and Klamath Mountains, California, USA." *Remote Sensing of Environment* 113: 645–656. https://doi.org/10.1016/j.rse.2008.11.009.

Miller, J. D., H. D. Safford, M. Crimmins, and A. E. Thode. 2009. "Quantitative Evidence for Increasing Forest Fire Severity in the Sierra Nevada and Southern Cascade Mountains, California and Nevada, USA." *Ecosystems* 12: 16–32. https://doi.org/10.1007/s10021-008-9201-9.

Miller, J. D., and A. E. Thode. 2007. “Quantifying Burn Severity in a Heterogeneous Landscape with a Relative Version of the Delta Normalized Burn Ratio (dNBR).” *Remote Sensing of Environment* 109: 66–80. https://doi.org/10.1016/j.rse.2006.12.006.

Miller, R. K., C. B. Field, and K. J. Mach. 2020. “Barriers and Enablers for Prescribed Burns for Wildfire Management in California.” *Nature Sustainability* 3: 101–9. https://doi.org/10.1038/s41893-019-0451-7.

Moomaw, W. R., S. A. Masino, and E. K. Faison. 2019. “Intact Forests in the United States: Proforestation Mitigates Climate Change and Serves the Greatest Good.” *Frontiers in Forests and Global Change* 2: 1–10. https://doi.org/10.3389/ffgc.2019.00027.

Nagel, T. A., and A. H. Taylor. 2005. “Fire and Persistence of Montane Chaparral in Mixed Conifer Forest Landscapes in the Northern Sierra Nevada, Lake Tahoe Basin, California, USA.” *Journal of the Torrey Botanical Society* 132: 442–457. https://doi.org/10.3159/1095-5674(2005)132[442:FAPOMC]2.0.CO;2.

National Park Service. 2022. “Sequoia and Kings Canyon National Parks Taking Emergency Action to Protect Giant Sequoias – Sequoia & Kings Canyon National Parks (U.S. National Park Service).” https://www.nps.gov/seki/learn/news/sequoia-and-kings-canyon-national-parks-taking-emergency-action-to-protect-giant-sequoias.htm.

North, M., B. M. Collins, H. Safford, and N. Stephenson. 2016. “Montane Forests.” In *Ecosystems of California* 553–578. Berkeley, CA: University of California Press.

North, M., B. M. Collins, and S. Stephens. 2012. “Using Fire to Increase the Scale, Benefits, and Future Maintenance of Fuels Treatments.” *Journal of Forestry* 110: 392–401. https://doi.org/10.5849/jof.12-021.

North, M., P. Stine, K. O’Hara, W. Zielinski, and S. Stephens. 2009. *An Ecosystem Management Strategy for Sierran Mixed-Conifer Forests (No. PSW-GTR-220)*. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. https://doi.org/10.2737/PSW-GTR-220.

North, M. P., S. M. Bisbing, D. L. Hankins, P. F. Hessburg, M. D. Hurteau, L. N. Kobziar, M. D. Meyer, A. E. Rhea, S. L. Stephens, and C. S. Stevens-Rumann. 2024. “Strategic Fire Zones Are Essential to Wildfire Risk Reduction in the Western United States.” *Fire Ecology* 20: 50. https://doi.org/10.1186/s42408-024-00282-y.

NPS. 2024. “National Park Service Complete Treatment Perimeters.” https://nifc.maps.arcgis.com/home/item.html?id=51f9750534c64b1d94b65d1fd2ff7d2f.

Ohlmann, J. L., and M. J. Gregory. 2002. “Predictive Mapping of Forest Composition and Structure with Direct Gradient Analysis and Nearest Neighbor Imputation in Coastal Oregon, U.S.A.” *Canadian Journal of Forest Research* 32: 725–741.

Ott, J. E., F. F. Kilkenny, and T. B. Jain. 2023. “Fuel Treatment Effectiveness at the Landscape Scale: A Systematic Review of Simulation Studies Comparing Treatment Scenarios in North America.” *Fire Ecology* 19: 10. https://doi.org/10.1186/s42408-022-00163-2.

Ouzts, J., T. Kolb, D. Huffman, and A. Sánchez Meador. 2015. “Post-Fire Ponderosa Pine Regeneration with and without Planting in Arizona and New Mexico.” *Forest Ecology and Management* 354: 281–290. https://doi.org/10.1016/j.foreco.2015.06.001.

ParcelQuest. 2023. “ParcelQuest Parcel Ownership Database.” https://www.parcelquest.com/.

Parks, S. A., and J. T. Abatzoglou. 2020. “Warmer and Drier Fire Seasons Contribute to Increases in Area Burned at High Severity in Western US Forests from 1985 to 2017.” *Geophysical Research Letters* 47: e2020GL089858. https://doi.org/10.1029/2020GL089858.

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: 1478–92. https://doi.org/10.1890/14-1430.1.

Parks, S. A., L. M. Holsinger, M. A. Voss, R. A. Loehman, and N. P. Robinson. 2018. “Mean Composite Fire Severity Metrics Computed with Google Earth Engine Offer Improved Accuracy and Expanded Mapping Potential.” *Remote Sensing* 10: 879. https://doi.org/10.3390/rs10060879.

Plumas National Forest. 2023. *North Fork Forest Recovery Project Proposed Action and Purpose and Need*. Plumas County, CA: USDA Forest Service, Mt. Hough Ranger District. https://www.fs.usda.gov/project/?project=64028.

Plumas National Forest. 2024. *Tributaries Forest Recovery Project (PALS #63289) Purpose and Need and Proposed Action*. Plumas County, CA: USDA Forest Service. https://www.fs.usda.gov/project/?project=63289.

Prichard, S. J., P. F. Hessburg, R. K. Hagmann, N. A. Povak, S. Z. Dobrowski, M. D. Hurteau, V. R. Kane, et al. 2021. “Adapting Western North American Forests to Climate Change and Wildfires: 10 Common Questions.” *Ecological Applications* 31: e02433. https://doi.org/10.1002/eap.2433.

Prichard, S. J., D. L. Peterson, and K. Jacobson. 2010. “Fuel Treatments Reduce the Severity of Wildfire Effects in Dry Mixed Conifer Forest, Washington, USA.” *Canadian Journal of Forest Research* 40: 1615–26.

Prichard, S. J., N. A. Povak, M. C. Kennedy, and D. W. Peterson. 2020. “Fuel Treatment Effectiveness in the Context of Landform, Vegetation, and Large, Wind-Driven Wildfires.” *Ecological Applications* 30: e02104. https://doi.org/10.1002/eap.2104.

Quinn-Davidson, L. N., J. M. Varner, L. N. Quinn-Davidson, and J. M. Varner. 2011. “Impediments to Prescribed Fire across Agency, Landscape and Manager: An Example from Northern California.” *International Journal of Wildland Fire* 21: 210–18. https://doi.org/10.1071/WF11017.

R Core Team. 2023. *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing.

Regrid. 2023. “Regrid Parcel Ownership Database.” https://regrid.com/.

Riddle, A. A. 2020. *Federal Wildfire Management: Ten-Year Funding Trends and Issues (FY2011-FY2020) (Congressional Research Service Report Prepared for Members and Committees of Congress No. R46583)*. Washington, D.C: Congressional Research Service. https://crsreports.congress.gov/product/pdf/R/R46583.

Russell, W. H., J. McBride, and R. Rowntree. 1998. “Revegetation after Four Stand-Replacing Fires in the Lake Tahoe Basin.” *Madroño* 45: 40–46.

Sadek, M. 2024. “California Proposes Millions to Make Firefighter Hand Crews Permanent.” ABC 7 KRCR Online. https://krcrtv.

com/news/local/california-sets-aside-millions-for-permanent-firefighter-hand-crews.

Safford, H. D., and J. T. Stevens. 2017. *Natural Range of Variation (NRV) for Yellow Pine and Mixed Conifer Forests in the Sierra Nevada, Southern Cascades, and Modoc and Inyo National Forests, California, USA. (General Technical Report No. PSW-GTR-256)*. Albany, CA: USDA Forest Service, Pacific Southwest Research Station.

Safford, H. D., J. T. Stevens, K. Merriam, M. D. Meyer, and A. M. Latimer. 2012. "Fuel Treatment Effectiveness in California Yellow Pine and Mixed Conifer Forests." *Forest Ecology and Management* 274: 17–28. https://doi.org/10.1016/j.foreco.2012.02.013.

Schultz, C. A., T. Jedd, and R. D. Beam. 2012. "The Collaborative Forest Landscape Restoration Program: A History and Overview of the First Projects." *Journal of Forestry* 110: 381–391. https://doi.org/10.5849/jof.11-082.

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. https://doi.org/10.1071/WF19040.

Schuurman, G. W., D. N. Cole, A. E. Cravens, S. Covington, S. D. Crausbay, C. H. Hoffman, D. J. Lawrence, et al. 2022. "Navigating Ecological Transformation: Resist–Accept–Direct as a Path to a New Resource Management Paradigm." *BioScience* 72: 16–29. https://doi.org/10.1093/biosci/biab067.

Scott, J. H., and R. E. Burgan. 2005. *Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model (General Technical Report No. RMRS-GTR-153)*. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. https://www.fs.usda.gov/treesearch/pubs/9521.

Scott, J. H., M. P. Thompson, and D. E. Calkin. 2013. *A Wildfire Risk Assessment Framework for Land and Resource Management (No. RMRS-GTR-315)*. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-GTR-315.

Sequoia National Forest and Giant Sequoia National Monument. 2023a. *Windy Fire Restoration Project Final Environmental Assessment*. Porterville, CA: U.S. Forest Service. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd1176505.pdf.

Sequoia National Forest and Giant Sequoia National Monument. 2023b. *Castle Fire Ecological Restoration Environmental Assessment*. Porterville, CA: US Forest Service. https://www.fs.usda.gov/project/?project=59292.

Shive, K., C. Knight, K. L. Wilson, A. L. Steel, and C. K. Stanley. 2025. "Leveraging Wildfire to Augment Forest Management and Amplify Forest Resilience." Dataset. Dryad. https://doi.org/10.5061/dryad.ttdz08m7d.

Shive, K. L., C. Brigham, A. C. Caprio, and P. Hardwick. 2021. *2021 Fire Season Impacts to Giant Sequoias*. Three Rivers, CA: National Park Service. https://www.nps.gov/articles/000/2021-fire-season-impacts-to-giant-sequoias.htm.

Shive, K. L., M. Coppoletta, R. B. Wayman, A. K. Paulson, K. Wilson, J. T. Abatzoglou, S. J. Saberi, B. L. Estes, and H. D. Safford. 2024. "Thinning with Follow-Up Burning Treatments Have Increased Effectiveness at Reducing Severity in California's Largest Wildfire." *Forest Ecology and Management* 572: 1–13.

Shive, K. L., H. K. Preisler, K. R. Welch, H. D. Safford, R. J. Butz, K. L. O'Hara, and S. L. Stephens. 2018. "From the Stand Scale to the Landscape Scale: Predicting the Spatial Patterns of Forest Regeneration after Disturbance." *Ecological Applications* 28: 1626–39. https://doi.org/10.1002/eap.1756.

Shive, K. L., A. Wuenschel, L. J. Hardlund, S. Morris, M. D. Meyer, and S. M. Hood. 2022. "Ancient Trees and Modern Wildfires: Declining Resilience to Wildfire in the Highly Fire-Adapted Giant Sequoia." *Forest Ecology and Management* 511: 120110. https://doi.org/10.1016/j.foreco.2022.120110.

Soderberg, D. N., A. J. Das, N. L. Stephenson, M. D. Meyer, C. A. Brigham, and J. Flickinger. 2024. "Assessing Giant Sequoia Mortality and Regeneration Following High-Severity Wildfire." *Ecosphere* 15: e4789. https://doi.org/10.1002/ecs2.4789.

Sorenson, Q. M., D. J. N. Young, and A. M. Latimer. 2025. "Tree Planting Outcomes after Severe Wildfire Depend on Climate, Competition, and Priority." *Forest Ecology and Management* 575: 122346. https://doi.org/10.1016/j.foreco.2024.122346.

State of California. 2020. "Executive Order (No. N-81-20)." https://www.gov.ca.gov/wp-content/uploads/2020/09/9.25.20-EO-N-81-20-signed.pdf.

State of California. 2022. "The 2022–23 Budget: Wildfire and Forest Resilience Package." https://lao.ca.gov/Publications/Report/4495.

Steel, Z. L., A. M. Fogg, R. Burnett, L. J. Roberts, and H. D. Safford. 2022. "When Bigger isn't Better—Implications of Large High-Severity Wildfire Patches for Avian Diversity and Community Composition." *Diversity and Distributions* 28: 439–453. https://doi.org/10.1111/ddi.13281.

Steel, Z. L., D. Foster, M. Coppoletta, J. M. Lydersen, S. L. Stephens, A. Paudel, S. H. Markwith, K. Merriam, and B. M. Collins. 2021. "Ecological Resilience and Vegetation Transition in the Face of Two Successive Large Wildfires." *Journal of Ecology* 109: 3340–55. https://doi.org/10.1111/1365-2745.13764.

Steel, Z. L., G. M. Jones, B. M. Collins, R. Green, A. Koltunov, K. L. Purcell, S. C. Sawyer, et al. 2023. "Mega-Disturbances Cause Rapid Decline of Mature Conifer Forest Habitat in California." *Ecological Applications* 33: e2763. https://doi.org/10.1002/eap.2763.

Steel, Z. L., J. E. D. Miller, L. C. Ponisio, M. W. Tingley, K. Wilkin, R. Blakey, K. M. Hoffman, and G. Jones. 2024. "A Roadmap for Pyrodiversity Science." *Journal of Biogeography* 51: 280–293. https://doi.org/10.1111/jbi.14745.

Steel, Z. L., H. D. Safford, and J. H. Viers. 2015. "The Fire Frequency-Severity Relationship and the Legacy of Fire Suppression in California Forests." *Ecosphere* 6(8): 1–23. https://doi.org/10.1890/ES14-00224.1.

Stephens, S. L., A. A. Bernal, B. M. Collins, M. A. Finney, C. Lautenberger, and D. Saah. 2022. "Mass Fire Behavior Created by Extensive Tree Mortality and High Tree Density Not Predicted by Operational Fire Behavior Models in the Southern Sierra Nevada." *Forest Ecology and Management* 518: 120258. https://doi.org/10.1016/j.foreco.2022.120258.

Stephens, S. L., D. E. Foster, J. J. Battles, A. A. Bernal, B. M. Collins, R. Hedges, J. J. Moghaddas, A. T. Roughton, and R. A. York. 2024. "Forest Restoration and Fuels Reduction Work: Different Pathways for Achieving Success in the Sierra

Nevada." *Ecological Applications* 34: e2932. https://doi.org/10.1002/eap.2932.

Stephens, S. L., J. J. Moghaddas, C. Edminster, C. E. Fiedler, S. Haase, M. Harrington, J. E. Keeley, et al. 2009. "Fire Treatment Effects on Vegetation Structure, Fuels, and Potential Fire Severity in Western U.S. Forests." *Ecological Applications* 19: 305–320. https://doi.org/10.1890/07-1755.1.

Stephens, S. L., and L. W. Ruth. 2005. "Federal Forest Policy in the United States." *Ecological Applications* 15: 532–542.

Stephens, S. L., S. Thompson, G. Boisramé, B. M. Collins, L. C. Ponisio, E. Rakhmatulina, Z. L. Steel, J. T. Stevens, J. W. Van Wagtendonk, and K. Wilkin. 2021. "Fire, Water, and Biodiversity in the Sierra Nevada: A Possible Triple Win." *Environmental Research Communications* 3: 081004. https://doi.org/10.1088/2515-7620/ac17e2.

Stephenson, N. L. 1999. "Reference Conditions for Giant Sequoia Forest Restoration: Structure, Process, and Precision." *Ecological Applications* 9: 1253–65. https://doi.org/10.1890/1051-0761(1999)009[1253:RCFGSF]2.0.CO;2.

Stephenson, N. L., and C. Brigham. 2021. *Preliminary Estimates of Sequoia Mortality in the 2020 Castle Fire*. Three Rivers, CA: National Park Service, Sequoia and Kings Canyon National Parks. https://www.nps.gov/articles/000/preliminary-estimates-of-sequoia-mortality-in-the-2020-castle-fire.htm.

Stephenson, N. L., A. J. Das, N. J. Ampersee, K. G. Cahill, A. C. Caprio, J. E. Sanders, and A. P. Williams. 2018. "Patterns and Correlates of Giant Sequoia Foliage Dieback during California's 2012–2016 Hotter Drought." *Forest Ecology and Management* 419: 268–278. https://doi.org/10.1016/j.foreco.2017.10.053.

Stevens, J. T., B. M. Collins, J. D. Miller, M. P. North, and S. L. Stephens. 2017. "Changing Spatial Patterns of Stand-Replacing Fire in California Conifer Forests." *Forest Ecology and Management* 406: 28–36.

Stevens, J. T., C. M. Haffey, J. D. Coop, P. J. Fornwalt, L. Yocom, C. D. Allen, A. Bradley, et al. 2021. "Tamm Review: Postfire Landscape Management in Frequent-Fire Conifer Forests of the Southwestern United States." *Forest Ecology and Management* 502: 119678. https://doi.org/10.1016/j.foreco.2021.119678.

Stevens-Rumann, C. S., K. B. Kemp, P. E. Higuera, B. J. Harvey, M. T. Rother, D. C. Donato, P. Morgan, and T. T. Veblen. 2018. "Evidence for Declining Forest Resilience to Wildfires under Climate Change." *Ecology Letters* 21: 243–252. https://doi.org/10.1111/ele.12889.

Stevens-Rumann, C. S., and P. Morgan. 2019. "Tree Regeneration Following Wildfires in the Western US: A Review." *Fire Ecology* 15: 15. https://doi.org/10.1186/s42408-019-0032-1.

Stewart, J., Y. Zhao, and J. Wright. 2024. "Climate-Adapted Seed Tool." https://reforestationtools.org/climate-adapted-seed-tool/.

Stewart, J. A. E., P. J. Van Mantgem, D. J. N. Young, K. L. Shive, H. K. Preisler, A. J. Das, N. L. Stephenson, et al. 2021. "Effects of Postfire Climate and Seed Availability on Postfire Conifer Regeneration." *Ecological Applications* 31: e02280. https://doi.org/10.1002/eap.2280.

Stillman, A. N., R. B. Siegel, R. L. Wilkerson, M. Johnson, C. A. Howell, and M. W. Tingley. 2019. "Nest Site Selection and Nest Survival of Black-Backed Woodpeckers after Wildfire." *The Condor* 121: duz039. https://doi.org/10.1093/condor/duz039.

Swain, D. L., J. T. Abatzoglou, C. Kolden, K. Shive, D. A. Kalashnikov, D. Singh, and E. Smith. 2023. "Climate Change Is Narrowing and Shifting Prescribed Fire Windows in Western United States." *Communications Earth & Environment* 4: 1–14. https://doi.org/10.1038/s43247-023-00993-1.

Swetnam, T. W. 1993. "Fire History and Climate Change in Giant Sequoia Groves." *Science* 262: 885–89. https://doi.org/10.1126/science.262.5135.885.

Taylor, A. H., L. B. Harris, and C. N. Skinner. 2022. "Severity Patterns of the 2021 Dixie Fire Exemplify the Need to Increase Low-Severity Fire Treatments in California's Forests." *Environmental Research Letters* 17: 071002. https://doi.org/10.1088/1748-9326/ac7735.

Thompson, C., H. Smith, R. Green, S. Wasser, and K. Purcell. 2021. "Fisher Use of Postfire Landscapes: Implications for Habitat Connectivity and Restoration." *Western North American Naturalist* 812(81): 225–242. https://doi.org/10.3398/064.081.0207.

Tubbesing, C. L., D. L. Fry, G. B. Roller, B. M. Collins, V. A. Fedorova, S. L. Stephens, and J. J. Battles. 2019. "Strategically Placed Landscape Fuel Treatments Decrease Fire Severity and Promote Recovery in the Northern Sierra Nevada." *Forest Ecology and Management* 436: 45–55. https://doi.org/10.1016/j.foreco.2019.01.010.

U.S. Department of the Interior. 2024. "President's 2025 Budget Proposes Significant Investments to Address the Nation's Wildfire Crisis and Advance Wildland Fire Workforce Reform." https://www.doi.gov/wildlandfirenews/presidents-2025-budget-proposes-significant-investments-address-nations-wildfire.

U.S. Fish and Wildlife Service. 2020. "Endangered and Threatened Wildlife and Plants; Endangered Species Status for Southern Sierra Nevada Distinct Population Segment of Fisher." Federal Register. https://www.federalregister.gov/documents/2020/05/15/2020-09153/endangered-and-threatened-wildlife-and-plants-endangered-speciesstatus-for-southern-sierra-nevada.

U.S. Fish and Wildlife Service. 2023. "Endangered and Threatened Wildlife and Plants; California Spotted Owl; Endangered Status for the Coastal-Southern California Distinct Population Segment and Threatened Status With Section 4(d) Rule for the Sierra Nevada Distinct Population Segment." https://www.federalregister.gov/documents/2023/02/23/2023-03526/endangered-and-threatened-wildlife-and-plants-california-spotted-owl-endangered-status-for-the.

U.S. Forest Service. 2000. *California Vegetation (CALVEG) Database*. McClellan, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station.

U.S. Forest Service. 2006. *Guidance on Limited Operating Periods for the California Spotted Owl* 5. Vallejo, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprd3812313.pdf.

U.S. Forest Service. 2018a. *California Vegetation (CALVEG) Existing Vegetation: EVeg Mid Region 5 South Sierra*. McClellan, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. https://www.fs.usda.gov/detail/r5/landmanagement/resourcemanagement/?cid=stelprdb5347192.

U.S. Forest Service. 2018b. *Vegetation Burn Severity Using the Composite Burn Index, 1984–2017 (VegBurnSeverity.Shp)*

(ESRI Shapefile). McClellan, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. https://www.fs.usda.gov/detail/r5/landmanagement/gis/?cid=stelprdb5327833.

U.S. Forest Service. 2019. *California Vegetation (CALVEG) Existing Vegetation: EVeg Mid Region 5 North Sierra*. McClellan, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. https://www.fs.usda.gov/detail/r5/landmanagement/resourcemanagement/?cid=stelprdb5347192.

U.S. Forest Service. 2021. "Bipartisan Infrastructure Law." https://www.usda.gov/infrastructure.

U.S. Forest Service. 2022a. "Wildfire Crisis Strategy: Confronting the Wildfire Crisis." https://www.fs.usda.gov/sites/default/files/fs_media/fs_document/Confronting-the-Wildfire-Crisis.pdf.

U.S. Forest Service. 2022b. *Wildfire Crisis Landscape Investments (No. FS-1187d)*. Washington, DC: USDA Forest Service. https://www.fs.usda.gov/sites/default/files/fs_media/fs_document/WCS-Initial-Landscapes.pdf.

U.S. Forest Service. 2022c. *National Prescribed Fire Program Review*. Washington, DC: U.S. Department of Agriculture, Forest Service. https://lessonslearned-prod-media-bucket.s3.us-gov-west-1.amazonaws.com/s3fs-public/2023-02/National%20Prescribed%20Fire%20Program%20Review-2022.pdf.

U.S. Forest Service. 2023a. "Hazard Fuels Treatments Database: S_USA.Activity_HazFuelTrt_PL.Shp." https://data.fs.usda.gov/geodata/edw/datasets.php.

U.S. Forest Service. 2023b. "Timber Harvest Database: S_USA.Activity_TimberHarvest.Shp." https://data.fs.usda.gov/geodata/edw/datasets.php.

U.S. Geological Survey. 2023. "Watershed Boundary Dataset Data Model (v2.3.1)." https://apps.nationalmap.gov/downloader/#/.

U.S. Geological Survey. 2024. "National Fire Plan Operations and Reporting System." https://usgs.nfpors.gov/NFPORS/index.html.

U.S. Geological Survey Gap Analysis Project. 2024. "Protected Areas Database of the United States (PAD-US) 4.0: U.S. Geological Survey Data Release." https://doi.org/10.5066/P96WBCHS.

USDA and USDI. 1995. *USDA and USDI (1995) Federal Wildland Fire Management Policy and Program Review*. Washington, DC: U.S. Department of Agriculture, U.S. Department of the Interior. https://www.forestsandrangelands.gov/documents/strategy/foundational/1995_fed_wildland_fire_policy_program_report.pdf.

Van de Water, K. M., and H. D. Safford. 2011. "A Summary of Fire Frequency Estimates for California Vegetation before Euro-American Settlement." *Fire Ecology* 7: 26–58. https://doi.org/10.4996/fireecology.0703026.

Van Wagtendonk, J. W., and J. A. Lutz. 2007. "Fire Regime Attributes of Wildland Fires in Yosemite National Park, USA." *Fire Ecology* 3: 34–52.

van Wagtendonk, J. W., K. A. Wagtendonk, and A. E. Thode. 2012. "Factors Associated with the Severity of Intersecting Fires in Yosemite National Park, California, USA." *Fire Ecology* 7: 11–31. https://doi.org/10.4996/fireecology.0801011.

Venton, D. 2024. "Forest Service Halts Prescribed Burns in California. Is It Worth the Risk?" *KQED News*. https://www.kqed.org/science/1994972/forest-service-halts-prescribed-burns-california-worth-risk.

Weeks, J., J. E. D. Miller, Z. L. Steel, E. E. Batzer, and H. D. Safford. 2023. "High-Severity Fire Drives Persistent Floristic Homogenization in Human-Altered Forests." *Ecosphere* 14: e4409. https://doi.org/10.1002/ecs2.4409.

Welch, K. R., H. D. Safford, and T. P. Young. 2016. "Predicting Conifer Establishment Post Wildfire in Mixed Conifer Forests of the North American Mediterranean-Climate Zone." *Ecosphere* 7: 1–29. https://doi.org/10.1002/ecs2.1609.

Williams, J. N., H. D. Safford, N. Enstice, Z. L. Steel, and A. K. Paulson. 2023. "High-Severity Burned Area and Proportion Exceed Historic Conditions in Sierra Nevada, California, and Adjacent Ranges." *Ecosphere* 14: e4397. https://doi.org/10.1002/ecs2.4397.

Wu, X., E. Sverdrup, M. D. Mastrandrea, M. W. Wara, and S. Wager. 2023. "Low-Intensity Fires Mitigate the Risk of High-Intensity Wildfires in California's Forests." *Science Advances* 9: eadi4123. https://doi.org/10.1126/sciadv.adi4123.

Young, D. J. N., J. T. Stevens, J. M. Earles, J. Moore, A. Ellis, A. L. Jirka, and A. M. Latimer. 2017. "Long-Term Climate and Competition Explain Forest Mortality Patterns under Extreme Drought." *Ecology Letters* 20: 78–86. https://doi.org/10.1111/ele.12711.

SUPPORTING INFORMATION

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

How to cite this article: Shive, Kristen L., Clarke A. Knight, Zachary L. Steel, Charlotte K. Stanley, and Kristen N. Wilson. 2025. "Leveraging Wildfire to Augment Forest Management and Amplify Forest Resilience." *Ecosphere* 16(6): e70306. https://doi.org/10.1002/ecs2.70306