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The state of the giant sequoias: losses, risks, and opportunities

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Abstract

Background Giant sequoias, an iconic tree found only in a narrow band along the western slope of the Sierra Nevada of California, are facing unprecedented threats. Despite being adapted to fire and resistant to both drought and insect attack, the species has exhibited signs of vulnerability to these stressors in recent years, with the most substantial impacts coming from wildfire. Recently, several unprecedentedly large and severe fires have resulted in the deaths of many large trees and, in some cases, limited postfire regeneration. These impacts have led to heightened efforts by managers to implement treatments to protect those places that are still vulnerable. Here, we provide a comprehensive, range-wide assessment of the condition of the species, including an evaluation of the trends in wildfire and its effects on large giant sequoia mortality and the potential for local extirpation, treatment patterns, and vulnerability to future fire.

Results From 2015 to 2024, 82% of giant sequoia grove area burned in wildfire, compared to 24% between 1910 and 2014. We conservatively estimate that 17.6% of all large giant sequoias have been killed by wildfire since 1984, with most dying in 2020 and 2021. Due to very severe wildfire, roughly 13% of the range is at some risk of local extirpation due to the loss of mature trees and limited predicted regeneration. Treatment activity has increased since 1995, with treatment type and amount varying by jurisdiction. The combination of treatment and wildfire has created a mosaic of resistance to severe fire, with 26% of grove area at high resistance, 38% at moderate resistance, 2% at low resistance, and 16% having no resistance. The remaining 18% are areas where mature giant sequoia forest was lost due to high severity fire.

Conclusions Giant sequoias have experienced substantial losses due to recent wildfire, with large areas at risk of grove loss. However, most burned area had lower severity effects, creating opportunities to leverage wildfire as a treatment. When combined with areas of active management, these opportunities can promote giant sequoia conservation in a time of rapid change.

Keywords Giant sequoia, High severity fire, Fuel reduction treatments, Wildland fire, Wildfire

Resumen

Antecedentes Las secuoyas gigantes, árboles icónicos que se encuentran sólo en una angosta franja a lo largo de la ladera oeste de la Sierra Nevada de California, están recibiendo amenazas sin precedentes. A pesar de estar adaptadas al fuego y ser resistentes tanto a la sequía como a los ataques de insectos, esta especie está exhibiendo signos de vulnerabilidad a esos factores estresantes en los últimos tiempos, con los impactos más sustanciales provenientes de

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los incendios. Recientemente, incendios grandes y severos sin precedentes conocidos, han resultado en la muerte de algunos árboles grandes, y, en algunos casos, han limitado su regeneración en el post fuego. Estos impactos han llevado a aumentar los esfuerzos de los gestores de recursos para implementar tratamientos y proteger aquellas áreas que son todavía vulnerables. En este trabajo, proveemos de una determinación comprensiva y de un amplio rango sobre la condición de esta especie, incluyendo una evaluación de las tendencias en los incendios de vegetación y sus efectos en la mortalidad de estas secuoyas gigantes y el potencial para su erradicación local, los patrones de tratamiento, y su vulnerabilidad a futuros incendios.

Resultados Desde 2015 a 2024, el 82% de los bosques dominados por grandes secuoyas gigantes, se quemaron en diferentes incendios, comparado con el 24% que se quemaron entre 1910 y 2014. Estimamos de manera conservativa que aproximadamente el 18% de las grandes secuoyas gigantes fueron quemadas por incendios desde 1984, la mayoría de ellas muriendo entre 2020 y 2021. Debido a fuegos muy severos, alrededor del 13% del hábitat de las secuoyas, se encuentran en riesgo de erradicación local debido a la pérdida de árboles maduros y una regeneración probablemente limitada. La actividad de realización de tratamientos se incrementó desde 1995, con tipos de tratamientos y su cantidad variando en función de la jurisdicción. La combinación de estos tratamientos y los efectos de los incendios ha creado un mosaico de resistencia a fuegos severos, con el 26% del hábitat de las secuoyas presentando una alta resistencia a fuegos de alta severidad, un 38% mostrando una mediana resistencia, un 2% una baja resistencia, y un 16% sin ninguna resistencia. El otro 18% lo representan áreas donde secuoyas gigantes maduras se perdieron debido a incendios de alta severidad.

Conclusiones Las secuoyas gigantes han experimentado pérdidas sustanciales debido a incendios recientes, con muchas áreas de esta especie en riesgo de perder su hábitat. Sin embargo, en la mayoría de las áreas quemadas, el efecto de la severidad fue bajo, lo que crea oportunidades para el uso del fuego como tratamiento. Cuando se combinan con áreas de manejo activo, estas oportunidades pueden promover la conservación de las secuoyas gigantes en tiempos cambiantes.

Introduction

Giant sequoias (*Sequoiadendron giganteum* (Lindl.) Buchholz) are among the oldest and largest organisms on earth, with individual giant sequoias living to >3000 years old (Hartesveldt et al. 1975). They also have a limited distribution, covering ~10,000 ha in the western Sierra Nevada mountains of California, USA. The ancient, iconic trees have been highly valued by humans for millennia (Franco 1994; Rueger 1994), and they have attracted visitors from across the globe for over a century (Tweed 2015). Their longevity has been attributed to their resistance to pests and disease, as well as adaptations to frequent low to moderate severity fire (Hartesveldt et al. 1975; Kilgore and Taylor 1979; Parsons and DeBenedetti 1979); until recently, the main cause of large giant sequoia mortality was toppling, often a consequence of successive fires that weakened their base. Yet, the past decade has seen a series of new threats for these iconic trees, raising concerns about the survival of the highly-valued ancient trees as well as the long-term persistence of the species within its current range (Nydick et al. 2018; Parsons and DeBenedetti 1979; Stephenson et al. 2018, 2024a). The historically unprecedented drought from 2012 to 2016 caused novel foliage dieback (Stephenson et al. 2018), and emerging drought-beetle-fire interactions may be contributing to the deaths of large, mature giant sequoias

(Foote et al. 2024). But arguably the most immediate threat to these ancient trees is the rapid increase in severe wildfire throughout the species' geographic range (Shive et al. 2022; Soderberg et al. 2024; Stephenson et al. 2024a).

Like many of the dry conifer forests of the western US, giant sequoia groves historically experienced frequent fires that resulted in lower severity fire effects (Swetnam 1993). These fires were ignited by Indigenous people tending the landscape or by lightning, and they were generally patchy, occurring roughly every 2 years at the scale of a large grove (~350 ha) and every ~15 years at the individual tree scale (Swetnam 1993; Swetnam et al. 2009). Giant sequoias have thick bark that insulates the cambium from fire and tall crowns that can escape surface fires. The species is also semi-serotinous, with the most successful establishment associated with very small patches (0.1 ha to a few ha) of higher intensity fire, which creates bare, ashy mineral soil and open sunny conditions (Hartesveldt et al. 1969; Stephenson 1996, 1999). In the past, these small pockets of high intensity likely primarily killed co-occurring conifers (e.g., white fir, incense cedar, and sugar pine) but very few large giant sequoias (Stephenson et al. 2024a). Fire exclusion began in earnest in the late nineteenth and early twentieth century with Euro-American colonization, ostensibly to protect the giant trees from wildfire.

As early as the 1960s, giant sequoia managers identified two of the most concerning consequences of prolonged fire exclusion (Parsons 1994): (1) the substantial accumulation of surface and ladder fuels, both of which could contribute to unnaturally severe wildfires (Biswell 1961, Biswell and Weaver 1968), and (2) the near-absence of natural giant sequoia regeneration (Hartseveldt and Harvey 1967; Harvey et al. 1980). To address these changes, managers called for restoring fire to the groves to reduce tree densities and woody surface fuels and to stimulate giant sequoia regeneration, with mechanical thinning used as an additional tool when necessary (Stephenson 1996; Stewart 1994). Over time, studies have corroborated the efficacy of such treatments in reducing the severity of subsequent wildfires in related forest types (Davis et al. 2019; Kalies and Yocom Kent 2016). Yet despite some initial optimism (Schuft 1973), progress in reversing the effects of fire exclusion in giant sequoia groves was relatively slow. By the mid-1990s, only about 18% of native grove area had been treated with prescribed fire and roughly another 6% by mechanical thinning, the latter of which was usually followed by planting of giant sequoias and other conifer seedlings (Stephenson 1996). As of ~2010, 90% of groves exhibited high or extreme fire return interval departure, which created forest conditions characterized by elevated tree densities and surface fuels (York et al. 2013).

While total grove area treated remained relatively small, so, initially did the areas affected by wildfires (Stephenson 1996; Meyer and Safford 2011). The few wildfires that entered giant sequoia groves were relatively easily contained, and few mature giant sequoias were killed. By the mid-2010s, however, periodic bouts of historically severe drought and heat set the stage for more extensive and severe wildfires, both by adding to fuel loads through the death of millions of trees (Northrop et al. 2024; Stephens et al. 2022) and by contributing to exceptionally low fuel moisture and extreme fire weather (Abatzoglou and Williams 2016; Williams et al. 2019).

Over the last 10 years, six historically unprecedented wildfires—in 2015, 2017, 2020, and 2021—were particularly devastating to giant sequoia groves, killing a substantial number of large, mature giant sequoias across much of their native range (Shive et al. 2021, 2022; Soderberg et al. 2024; Stephenson and Brigham 2021). Mortality at this scale was unprecedented over at least the last 1000 years and probably much longer (Stephenson et al. 2024a). These losses are especially troubling given that more than 20% of large giant sequoias were already lost to extractive logging in the late nineteenth to early twentieth centuries (Stephenson 1996). In addition to the loss of large, mature giant sequoias, the recent fires may reduce the overall extent of giant sequoia populations

because, although small pockets of higher intensity fire are needed for giant sequoia regeneration and establishment, the extent of high severity crown fire in recent years has been associated with post-fire giant sequoia seedling densities well below historical levels (Soderberg et al. 2024). Where areas of limited regeneration are also out of the dispersal zone of surviving trees, there is particular concern around local extirpation of the species.

Given giant sequoias' limited distribution and potential for ongoing loss, an understanding of the cumulative impacts of this altered fire regime at range-wide scales is critically needed for restoration planning and prioritization. For example, recent reports suggest that an estimated 13–19% of all existing large giant sequoias (>1.1 m in diameter) were killed in the 2020 and 2021 wildfires (Shive et al. 2021; Stephenson and Brigham 2021). While this initial effort was informative, the extent of recent research and monitoring in the region provides an opportunity to improve on these estimates by using a much larger reference dataset, building a more robust modelling framework, and expanding these estimates to include mortality across more wildfires. In addition, areas of high mortality can be intersected with areas where seedling regeneration is expected to be limited (Soderberg et al. 2024) to estimate the risk of local extirpation from wildfire.

Given the potential for restoration treatments (primarily prescribed fire and mechanical thinning) to forestall these adverse high severity fire impacts, giant sequoia managers are working to increase the pace and scale of these treatments in response to the record-breaking 2020 and 2021 fire seasons (e.g., National Park Service 2022; US Forest Service 2022), but the extent to which this is happening across the range has not been quantified. Moreover, examining trends in treatment rates and types can elucidate differences among management entities and highlight opportunities to expand, diversify, and prioritize treatments range-wide. Simultaneously, there is increasing recognition that low to moderate severity areas of otherwise undesirable wildfires can be restorative (Larson et al. 2022; Meyer et al. 2021; North et al. 2021; Stevens et al. 2021). In these areas, large, mature giant sequoia survival is generally high (Shive et al. 2022), and surface and ladder fuels are reduced (Das et al. 2025). While the impacts of high severity fire have received significant management and research attention, the extent of this potentially beneficial wildfire is less well documented in giant sequoia. Moreover, both wildfires and treatments interact to shape current conditions, and disturbance history can be used to estimate the relative resistance to high severity fire (Shive et al. 2025) across the range, which will also be an important consideration in prioritizing future treatments.

To better understand trends and conditions across the giant sequoia range, we addressed the following questions:

1. What are the trends in wildfire history and severity, including beneficial wildfire, in giant sequoia groves?
2. What are the impacts of altered fire regimes on large giant sequoia mortality and, when considering expected regeneration patterns, what is the potential for local extirpation?
3. What are the trends in active forest management (i.e., prescribed fire, thinning) in giant sequoia groves, and how do these compare with beneficial wildfire?
4. How do treatments and wildfire interact to confer resistance to high severity fire across groves?

Methods

Study area

Giant sequoia groves occur within the mixed conifer forest zone on the western slope of the Sierra Nevada mountains, between 898 and 2680 m in elevation. In addition to giant sequoias, the groves include a range of other conifer species that commonly occur in the neighboring mixed conifer forests, typically including varying components of white fir (*Abies concolor* (Gordon & Glend.) Lindl. ex Hildebr.), sugar pine (*Pinus lambertiana* Douglas), incense cedar (*Calocedrus decurrens* (Torr.) Florin), ponderosa pine (*Pinus ponderosa* Douglas ex Lawson & C. Lawson), and black oak (*Quercus kelloggii* Newb.) (Rundel, 1971). The climate is mediterranean with hot, dry summers and cool, moist winters, where mean annual precipitation ranges from 960 to 1179 mm.

The natural range is bounded to the north by Placer Grove on the Tahoe National Forest and to the south by Deer Creek Grove in Giant Sequoia National Monument (GSNM), with 96% of the range area occurring south of the Kings River (Hart 2023; Fig. 1). The mapped area of giant sequoia extent has varied due to different mapping approaches, but a 2020 effort formalized agreed upon boundaries to support research and range-wide tracking (Hart 2023, though individual management entities may retain their own geographic boundaries that are associated with land management designations). All spatial analyses and results use the Hart (2023) boundaries, which cover ~10,133 ha across 97 distinct mapped populations or isolated trees, which are traditionally lumped to ~70 groves (grove numbers vary across sources, depending on how populations are lumped or split). There are a few additional groves that occur on the Tule River Indian Reservation, but spatial data on these are not publicly available. Our analysis is focused on the majority of the range, which is primarily in public ownership.

Table 1 reports the grove area managed by entity which was derived from rectified ownership boundaries in the California Protected Areas Database ((CPAD) GreenInfo Network, 2022). The sum of these hectares (10,137 ha) slightly exceeds the Hart (2023) mapped boundaries due to small areas of overlap between some neighboring agencies. The Supplementary Materials include a table of the Hart (2023) mapped populations and their managing entity (Appendix A, Table A1), as well as information on how the Hart (2023) boundaries were rectified with CPAD (Appendix B).

Table 1 also reports the total number of groves each managing entity recognizes, and the years for which treatment data are available (Table 1) (e.g., for USFS, the earliest treatment record in the Forest Service Activity Tracking System across the three management units was 1937, though this treatment was not in a giant sequoia grove, it reflects the time in which records began).

All spatial data were manipulated in R (R Core Team 2023) using the tidyverse (Wickham 2019), sf (Pebesma 2018; Pebesma and Bivand 2023), and terra (Hijmans 2025) packages.

Wildfire data

To evaluate area burned over the last century, we used a database of fire perimeters from California, starting in 1910, the first year a fire was recorded in a giant sequoia grove, through 2024 (CAL Fire 2023a). Note that records prior to ~1950 are likely less comprehensive and spatially accurate than the later records. We assessed trends in fire severity between 1984 and 2024, since fire severity data are based on Landsat imagery which first became available in 1984. We used Google Earth Engine to calculate the Relativized differenced Normalized Burn Ratio (RdNBR) to create extended assessment (e.g., roughly 1 year postfire) severity maps for each fire that occurred in a grove in this timeframe. RdNBR quantifies the change in vegetation condition based on mean pre- and postfire scenes, using 30-m resolution LANDSAT satellite imagery (Parks et al. 2018). We also used an existing immediate postfire severity assessment from the US Forest Service Rapid Assessment Vegetation Condition program for the 2024 Coffee Pot Fire, which is based on 20 m Sentinel imagery, since the analysis occurred too soon after the fire to obtain the extended assessment (the Coffee Pot Fire covered only 3% of the total fire severity dataset within giant sequoia groves). RdNBR was then classified into four severity classes using established thresholds for Sierra Nevada forests (Miller and Thode 2007). These classes include undetected change, low severity (>0–25% change in live vegetation), moderate severity (25–75% change), and high severity (75–100% change).

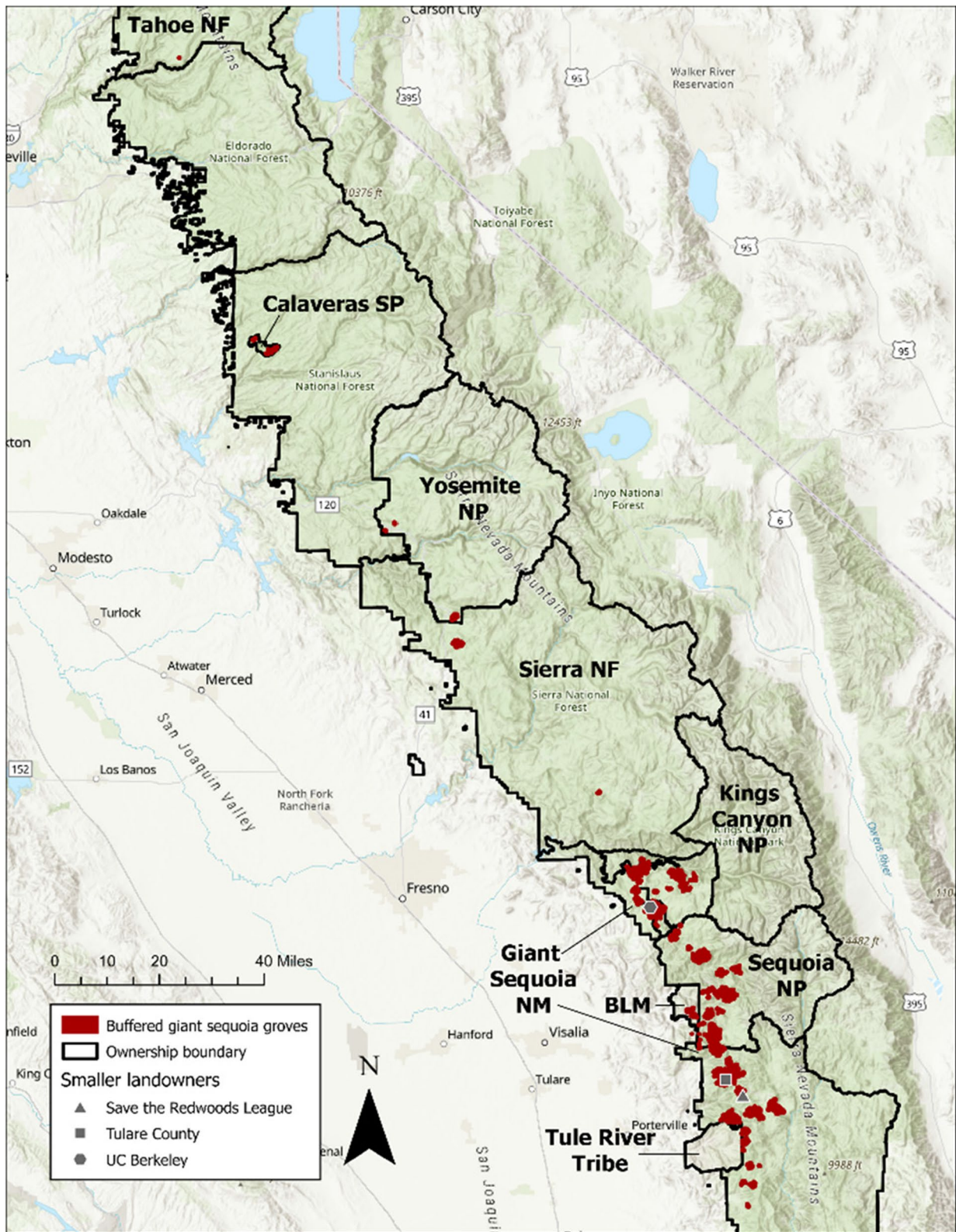


Fig. 1 The giant sequoia range with managing entity. Groves are buffered by 500 m to improve visibility. Mountain Home Demonstration State Forest, Save the Redwoods League, Tulare County and UC Berkeley boundaries are not visible at this scale. The Tule River Tribe also manages sequoia groves, but their grove locations are not publicly available

Table 1 Land managers of giant sequoia groves throughout the range and the grove extent that they manage in hectares based on Hart (2023) and the number of groves the agencies report that they manage. Treatment data availability refers to the time period during which the agency was recording any treatment data, regardless of whether or not it was in a grove. Details on the 16 grove units that span agency boundaries can be found in the Supplementary Materials (Appendix A, Table A1)

Managing agency/unit	Hectares (from Hart 2023)	Number of agency-recognized groves	Years with treatment data available
<i>Bureau of Land Management</i>			
Case Mountain Extensive Recreation Management Area	37	6	2011–2024
<i>California State Parks</i>			
Calaveras Big Trees State Park	172	2	2000–2024
<i>California Department of Forestry and Fire Protection (CAL FIRE)</i>			
Mountain Home Demonstration State Forest	985	Portions of 4	1951–2024
<i>National Park Service</i>			
Sequoia and Kings Canyon National Parks	4,146	39	1970–2024
Yosemite National Park	126	3	
<i>US Forest Service</i>			
Giant Sequoia National Monument	4,005	33	1937–2024
Sierra National Forest	153	2	
Tahoe National Forest	1	1	
<i>Tulare County</i>			
Balch Park	81	Portion of 1	None documented
<i>Non-profit</i>			
Save the Redwoods League	130	Portion of 1	1997–2024
<i>UC Berkeley</i>			
Whitaker's Research Forest	119	Portion of 1	2001–2024
<i>Private ownership</i>			
Miscellaneous owners	182	Portions of 13	1997–2024

The Case Mountain Groves have roughly 44 ha of private ownership which are managed by the BLM under existing agreements, but these hectares are shown under private ownership in this table

For high severity, the overall change metric has been linked with >90% basal area mortality for overstory trees (Miller et al. 2009). Note that in forested systems, undetected change means that the satellite did not detect a change in canopy conditions, which in some cases is a totally unburned area, and in other cases the area experienced a light underburn. Where we use the severity data in our regeneration and resistance classifications (described below), we took a conservative approach and treat the undetected change category as unburned. Our collated severity dataset included 37 total wildfires.

To more closely examine recent patterns of high severity, we used the *landscapemetrics* package (Hesselbarth et al. 2019) in R to calculate high severity patch sizes for all fires in our fire severity dataset (1984–2024). We used a 4-pixel neighborhood rule (where the pixels above, below, left, and right are also high severity) to define contiguous high severity patches, which may or may not have small lower severity patches inside them. These high severity patches were identified

across each of the fire areas and clipped to the grove boundaries.

Estimating large giant sequoia mortality

To estimate large giant sequoia mortality across burned areas, we built on the framework developed by Stephenson and Brigham (2021) and used in Shive et al. (2021), which collectively covered the 2020 and 2021 wildfires (the differences between these initial efforts and the current modelling are detailed in the Supplementary Materials, Appendix C). We focused on the mortality of “large giant sequoias” (defined as trees >107 cm (3.5′) diameter at breast height (DBH)) because they are highly culturally valued, and also produce the most cones (Sillett et al. 2019). Note that this classification is distinct from reproductive maturity, as many smaller trees have some cones with viable seeds; throughout the text, we use “large” giant sequoias when referring to the size class used for the mortality estimates, and “mature” when referring to concerns around regeneration.

We based our analysis on a large, combined dataset with data from Soderberg et al. (2024), Shive et al. (2022), Meyer et al. (2025), and additional unpublished data from Save the Redwoods League (SRL), University of California, Berkeley (UCB), and the University of Nevada-Reno. These data included the live/dead status for 3741 large giant sequoias, spanning 38 groves in eight different wildfires that occurred from 2015 to 2022 (Table 2). Note that the data from Shive et al. 2022, which is 12% of the total mortality dataset, used a slightly larger size cut off for their surveys (120 cm; $\sim 4'$). All field assessments occurred within 5 years following wildfire (Table 2). A 5-year post-fire window captures both immediate and some of the delayed fire-induced mortality (Shive et al. 2022), depending on the number of years postfire the measurements were taken. The 5-year window also minimizes the influence of background mortality due to natural causes, which is estimated to be roughly 0.1% annually for large giant sequoias (Lambert and Stohlgren 1988). Giant sequoias included in the dataset were sampled across a range of fire severity classes and multiple jurisdictions, including Sequoia and Kings Canyon National Parks (SEKI), Yosemite National Park (YOSE); GSNM; Mountain Home Demonstration State Forest (MHDSF); Sierra National Forest; and lands managed by SRL and UCB. Tree sizes across these datasets ranged from 107 to 950 cm, with a mean of 266 cm and a median of 243 cm. Note that the largest DBH in our dataset exceeds the largest diameter published for giant sequoia; we assume that this is due to the difficulty with measuring large giant sequoias in the field using conventional methods (e.g., DBH tapes).

We fit a Bayesian generalized additive model with a negative binomial family and logit link, which estimated a global spline representing the nonlinear RdNBR–mortality curve. The empirical dataset consisted of individual trees classified as alive or dead; the model used these observations to estimate mortality probabilities across the continuous RdNBR gradient. This approach

captures nonlinear severity responses while accounting for variance inflation common in ecological data, and is conceptually analogous to recent efforts to link continuous burn-severity metrics to mortality outcomes (e.g., Furniss et al. 2020; Greenler et al. 2023). Posterior predictive checks, performed by simulating new datasets from the fitted model and comparing them with observed patterns, showed close agreement between observed and replicated mortality statistics across the RdNBR range (Figs. C1–C2). In Fig. 4, we also plot empirical mortality proportions in 200-unit RdNBR bins against the model fit to illustrate model–data agreement. Full model specification, priors, and diagnostics are provided in Supplementary Material, Appendix C.

We then used RdNBR across the range to scale our estimates up to the total number of dead large giant sequoias, for all wildfires between 1984 and 2024. We used the expected density of 6.6867 large giant sequoias ha^{-1} (derived from the Sequoia Tree Inventory (National Park Service 1973) and grove boundaries (Hart 2023)) to estimate the number of large giant sequoias based on pixel area (determined by the sensor resolution: 30 m for Landsat, 20 m for Sentinel) and applied the RdNBR-based mortality model to estimate the number of trees killed. We then aggregated pixel-level results to estimate total large giant sequoia mortality per fire event. Considerations about how past logging may have impacted the density estimates, which came from predominantly old-growth forests, can be found in the Supplementary Material (Appendix C).

Estimating the risk of local extirpation

We classified the risk of local extirpation by considering both expected recent regeneration and the retention of live seed trees, where the extirpation risk could range from low (areas that retain mature live seed trees) to very high (areas that lack live seed trees postfire and that had little regeneration). We distinguished these classes based

Table 2 Number of large sequoias (> 107 cm DBH) that were surveyed in a given year postfire, for each wildfire. For the Rough, Pier and Railroad Fires (12% of the data), large sequoias were defined as > 120 cm DBH

Survey delay (years since fire)	Fire-year								Total
	Rough 2015	Pier 2017	Railroad 2017	Eden 2018	Castle 2020	KNP 2021	Windy 2021	Washburn 2022	
1	–	–	53	–	689	923	427	21	2100
2	–	–	–	–	220	111	4	–	335
3	–	205	–	–	540	60	1	–	806
4	–	–	–	–	170	–	–	–	183
5	196	–	–	121	–	–	–	–	317
Total trees	196	205	53	121	1619	1094	432	21	3741

on relationships between disturbance type, large tree mortality, and regeneration (Soderberg et al. 2024) for disturbances that occurred between 1984 and 2024. For both seed tree retention and expected regeneration, we further subdivided the high severity class into three subclasses (Table 3) to account for important variations in levels of tree mortality and regeneration as documented in Soderberg et al. (2024) and in our mortality analysis.

For regeneration, we classified areas with no fire or treatment as “effectively none” (Table 3), because successful establishment requires the bare mineral soil and forest gaps created by fire (Hartseveldt et al. 1969). This includes unburned areas and areas of undetected change within fire perimeters on severity maps (i.e., some of which may have had a light underburn). Within areas that had no recent fire history, areas that had mechanical thinning were classified as having “none to sparse, scattered patches.” Hand thinning or lop and scatter treatments that do not expose the soil are unlikely to promote regeneration (Stephens et al. 1999), but thinning treatments conducted with heavy equipment that expose bare mineral soil and create canopy gaps can promote some regeneration, since giant sequoias release some seed each year (Meyer and Safford 2011).

Within burned areas, regeneration tends to follow a hump-shaped curve, with the least regeneration in very low and very high severity areas (Soderberg et al. 2024; Stephenson 1994). We classified low and moderate severity areas as likely having “sparse, scattered patches to many patches” of regeneration; these areas can result in “many patches” even in low severity areas as some small, local higher-severity patches can go undetected by RdNBR (Stephenson et al. 2024b). We assigned the same expected regeneration for prescribed fire footprints presumed to be predominantly low severity.

Within high severity, we assigned expected regeneration based on established relationships with the type of crown damage (Soderberg et al. 2024; Soderberg and Das 2023). Crown scorch occurs when the foliage is killed, but not consumed, by radiant or convective heat. Crown torch results in direct needle combustion from a crown fire, and has been associated with the lowest regeneration rates (Soderberg et al. 2024), likely because the seeds are either burned up or subjected to lethal temperatures. Soderberg and Das (2023) linked individual giant sequoias with $\geq 90\%$ crown torch with ~ 1100 RdNBR, where the remaining crown was scorched or had $< 1\%$ live crown remaining (most had 0%). An RdNBR of ≥ 1100 also corresponds to a steep drop off in regeneration rates (Soderberg et al. 2024), so we classified areas > 1100 as having “sparse, scattered patches.” An RdNBR of ~ 800 corresponds to areas with $\sim 50\%$ crown torch (where the remaining crown is scorched or has $\leq 8\%$ live crown; Soderberg and Das (2023)), so we classified areas 800–1100 as having “scattered patches to many patches.” The lowest subclass within high severity was defined as RdNBR values 640–800, which were classified as being likely to have “many patches,” given observed regeneration patterns in crown scorch areas, where seed release was likely abundant and the increase in canopy openings can increase seedling survival.

For seed tree retention, unburned, low severity, and prescribed fire areas were all classified as “very high,” ranging down to “very low” in the highest severity areas (e.g., RdNBR > 1100 ; Table 3). Within the three high severity subclasses, we modified the classifications in Table 3 in high severity areas that are within the estimated dispersal distance of unburned or lesser burned areas as a proxy for seed tree retention. We used 67.8 m as the dispersal distance, which is where 99% of the giant sequoia seed rain is expected to fall (Clark et al. 1999). Where the high severity

Table 3 Expected patterns of recent regeneration and seed tree retention by treatment type and across a fire severity gradient. For disturbance types, active treatment is further subdivided by the coarse treatment types (mechanical treatments and fire-related treatments) and wildfire is subdivided by severity class (and high severity is further parsed out into three groups). Both recent regeneration and seed tree retention were then combined to estimate the potential risk of local giant sequoia extirpation

Disturbance type		Expected current natural regeneration	Seed tree retention	Risk of local extirpation
Untreated/unburned		Effectively none	Very high	Low
Active treatment	Mechanical treatments	None to sparse, scattered patches	Very high	Low
	Fire-related treatments	Sparse, scattered patches	Very high	Low
Wildfire	Undetected change	Effectively none	Very high	Low
	Low severity	Sparse, scattered patches	Very high	Low
	Moderate severity	Scattered patches to many patches	High to moderate	Low
	High severity	<i>RdNBR 640-800</i> <i>RdNBR 800-1100</i> <i>RdNBR >1100</i>	Many patches Scattered patches to many patches Sparse, scattered patches	Moderate Low Very low

areas are within this potential dispersal zone, we changed the class for seed tree retention by one qualitative level (e.g., areas of high severity that are expected to have “Low” seed tree retention were reassigned to “Moderate,” “Moderate” retention were reassigned to “High to Moderate”).

Finally, considering both the expected regeneration and seed tree retention patterns, we classified the range into the degree of risk of local extirpation as detailed in Table 3. We also overlaid federally designated wilderness boundaries to estimate how much of the area that is at risk is also potentially more difficult to access.

Treatment data

We used a suite of sources for the treatment data. For federal lands, we used a combination of publicly available datasets (National Park Service 2024; US Forest Service 2023a, b), which we supplemented with data directly from the agencies as needed (additional details in the Supplementary Materials, Appendix B). 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.

For private and state lands, we used the CAL FIRE Forest and Range Assessment Program prescribed fire database (CAL Fire 2023a), the CAL FIRE Timber Harvest Plan (THP) database (CAL Fire 2023b, c), the Interagency Tracking System, and data for MHDSF came from Phelan (2024). Note that we lack spatial data for single tree removal of beetle killed trees (2013–2018) (Jim Kral, MHDSF Forester, personal communication).

For private lands with no THPs, it is possible that some of these areas were treated under an exemption, which we cannot track. We also note that there was a Non-industrial Timber Management Plan (NTMP) from 1999 for 478 ha of Dillonwood Grove. However, NTMPs simply authorize a broad range of work but do not document if or where work has taken place, so we did not consider this area treated. In addition, Dillonwood grove became part of SEKI in 2000, so it is unlikely much treatment was done in one year. Private inholdings in the BLM Case Mountain Recreation Area groves have had some mechanical thinning and mastication treatments in conjunction with BLM treatments, which is included in the BLM mapped polygons (Danielle Thomas, BLM Forester, personal communication). For both the BLM Case Mountain Recreation Area groves and Calaveras Big Trees State Park, there were some past treatments ranging from the 1980s to early 2000s, but these were not documented spatially. In areas where some treatment data are lacking, our summary should be considered a conservative estimate.

We reclassified all treatment types into two coarse treatment classes: “Fire-related treatment,” which includes broadcast burning and pile burning. Pile

burning can be less effective at reducing subsequent wildfire severity (62% mean reduction versus 72% mean reduction for broadcast burning; Davis et al. 2024), likely because it does not reduce woody fuels continuously across the forest floor. However, the differences are not large and pile burning does reduce and consume some of the surface fuel, so we have combined these to simplify our assessment. Mechanical thinning via hand thinning or using heavy equipment were classified as “Mechanical treatments” (for a detailed crosswalk of treatment types, see Appendix S1, Table S1 in Shive et al. 2025). While there is tremendous variation in mechanical treatments, we combined them since their overall goal is tree density reduction without surface fuel consumption. For the bar graphs summarizing treatment over time, we report “activity hectares” sensu Knight et al. (2022), which refers to the total amount of treatment on an area basis, but did not distinguish if area (i.e., “footprint hectares”). We made this choice because, as noted above, one of our interests is in how much work can get done. Footprint hectares are considered as part of the classification of resistance to high severity fire, described below, and also discussed in the text.

Classifying resistance to high severity wildfire

Building on an assessment of forest resistance in the Sierra Nevada yellow pine and mixed conifer forests (Shive et al. 2025), we evaluated the potential resistance to high severity fire across the giant sequoia range in terms of stand-level fuel conditions (not the fire resistance of individual giant sequoias). We inferred this by disturbance history, including both past treatments and wildfires. We considered both the type, number, and timing of prior disturbances to estimate the state of giant sequoia groves as of 2024. Beneficial disturbances included low and moderate severity fire, fire-related treatments, and mechanical thinning.

We classified the range into six categories based on disturbance history, where disturbance efficacy was set at 15 years, so that the most recent disturbance had to occur within that time frame (2010–2024) for an area to have some level of resistance. Several studies suggest that treatments remain effective for ~10 years, but, as this is an approximation and can be site specific, we used 15 years to allow for some variation in effectiveness, and because it matches the historic fire return interval. We classified areas as having *High resistance* to high severity wildfire where they had (1) ≥ 2 disturbances that included either low or moderate severity fire, prescribed fire, pile burning or thinning, where at least one was a fire-related treatment that reduced surface fuels; and (2) the time between treatments was < 22 years (Fig. 2). Note that we



Fig. 2 Examples of the four resistance classes (No, Low, Moderate and High resistance) and mature forest loss

used a longer time frame for the maximum time *between* treatments (22 years, based on North et al. 2022) than time *since* treatment (15 years). We made the choice to

use different time intervals because while > 15 years since the last treatment may result in fuels conditions that lead to severe fire effects during the height of wildfire season,

if that area receives another treatment within 22 years before burning in a wildfire, the legacy effects of the first treatment are likely to persist and contribute to increased resistance (Stephens et al. 2012). This differs slightly from the similar classification in Shive et al. (2025) which used the 22-year window for both time since beneficial disturbance as well as time between treatments.

Because several studies have shown that prescribed fire-only treatments are more resistant to high severity fire than mechanical treatments alone (Davis et al. 2024; Prichard et al. 2020), we classified groves that have had only one fire treatment or beneficial wildfire as *Moderate resistance* (Fig. 2). We classified areas that have had only mechanical treatments (one or more) as *Low resistance*. Thinning-only treatments are generally the most variable in terms of their impact on subsequent fire severity; areas with excess fuels that were created by the treatment may burn more severely, whereas areas where those fuels were addressed as part of the prescription, could have neutral to positive effects (Davis et al. 2024; Kalies and Yocom Kent 2016; Prichard et al. 2021). For the sake of this exercise, we make the simplifying assumption that thinning-only treatments had a modest positive impact. Note that areas where > 22 years passed between treatments were classified based solely on the most recent disturbance, under the assumption that the extended time period between treatments negated the benefit of repeated treatments; therefore these areas were classified as Low or Moderate resistance (but we acknowledge that some of these areas that had multiple widely spaced out treatments may still be more resistant than areas with just one disturbance, depending on the site).

Areas with no treatments or areas within wildfires that were classified as undetected change during the period of analysis (2010–2024) were classified as *No resistance* (Fig. 2). No Resistance represents stand-level conditions that lack an inherent resistance to severe wildfire due to elevated fuels and dense forest structure; it does not imply that a grove will burn severely under all environmental conditions (e.g., nighttime, periods with higher fuel moisture). In other words, “No resistance” is simply an assessment of the fuels-based risk of high severity fire.

We further classified areas that burned at high severity as *Mature forest loss* (Fig. 2). For this class only, we included all areas that burned at high severity 1984–2024, since they would not have re-grown to mature giant sequoia forests in this timeframe, even if there was adequate postfire regeneration. Figure 2 includes photographic examples of forest structure and fuels for each of these classes. To understand where the benefits of restoration work have potentially been lost (i.e., “faded” resistance), we also classified areas where > 15 years have

passed since the last treatment for presentation in a separate figure.

Results

Q1: wildfire trends

Area burned (1910–2024)

The first recorded wildfire occurred in 1910, after the onset of fire exclusion and during the active suppression period. Between 1910 and 2024, 10,789 ha of giant sequoia grove area burned, which covered a total of 8514 footprint hectares (Supplementary Materials, Fig. A1).

Between 1910 and 2014, there were 70 wildfires documented within grove boundaries that burned a total of 2440 ha, which is 24% of the total grove area. During this period, the largest fire was 363 ha and the median wildfire size was 6 ha. Five wildfires burned more than 100 ha of giant sequoia forests (one in 1910, two in 1928, one in 1955, and one in 1991). These fires burned in Black Mountain Grove (1928), Freeman Creek Grove (1910), the mostly second growth Converse Basin Grove (1928 and 1955), and the East Fork Grove (1991; this wildfire was managed for resource benefit).

Between 2015 and 2024, 82% of giant sequoia grove area burned, with the onset of large wildfires beginning with the 2015 Rough Fire (Supplementary Materials, Fig. A1). This period includes 15 wildfires that burned 8349 ha, over three times more than burned between 1910 and 2014 (or 23 ha per year in 1910–2014 versus 835 ha per year in 2015 to 2024, which is a 36-fold increase in the rate of burning). Most of these fires were naturally ignited by lightning, and several of them were in the backcountry and were managed for resource benefit. However, the larger and more recent fires were managed primarily for suppression objectives. This included the 2020 Castle Fire that burned 3544 ha of giant sequoia groves, followed by the 2021 KNP Complex and Windy Fires that burned 2231 ha of grove area; these fires were also started by lightning, but they were burning under severe fire weather conditions.

Wildfire severity (1984–2024)

For the period when severity data are available (1984 to present), 9106 ha of giant sequoia grove area burned. Roughly 20% (1846 ha) of the fire areas were classified as high severity, most of which occurred in the latter part of the study period (2015, 2017, 2020 and 2021; Fig. 3). For the largest wildfires that also had the greatest area of high severity (2020 Castle Fire, 2021 KNP Complex, 2021 Windy Fire), the severity in individual groves varied. Some smaller groves such as Starvation Creek, Board Camp, and Deer Creek (all < 20 ha) were classified as > 85% high severity, with the 10 ha Starvation Creek grove classified as 96% high severity. Some larger groves

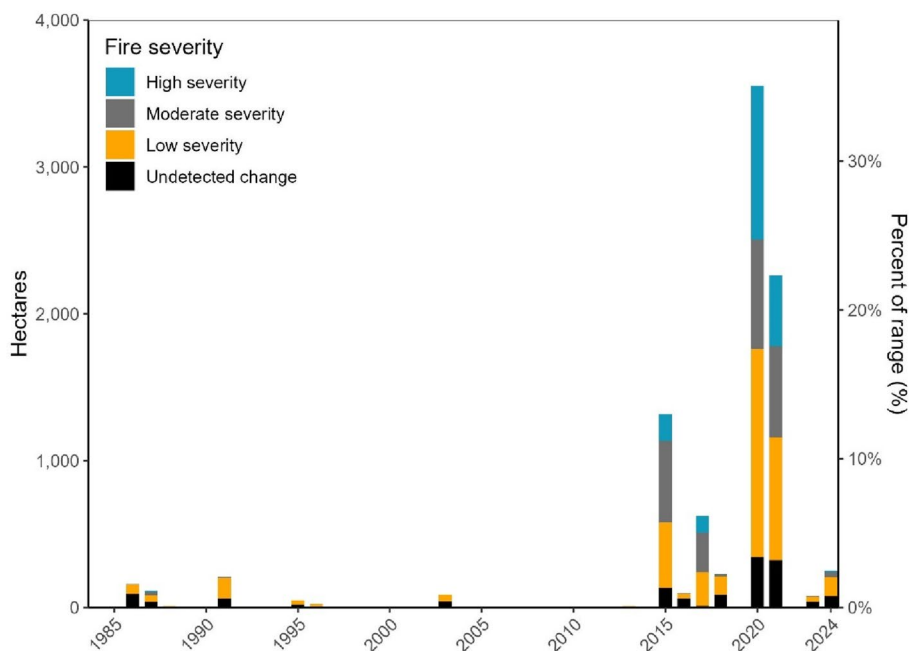


Fig. 3 Wildfire area burned by severity (left axis) and by the percentage of the giant sequoia range (right axis), 1984–2024. Note that several fire years are not visible due to the scale, including six years with < 1 ha burned, and 8 years with 1–11 ha burned

sustained very high proportions of area burned with high severity fire effects, including the 234 ha Wheel Meadow grove (79%) and the 572 ha Freeman Creek grove (64%). The two largest groves, Mountain Home (1133 ha) and Redwood Mountain (1059 ha), experienced a lower proportion of high severity (17% and 25% respectively), but these lower percentages still resulted in substantial total area impacted due to grove size.

For all wildfires during the 10-year period of 2015–2024, the largest contiguous patch of high severity wildfire was 265.7 ha, which was more than two orders of magnitude larger than the largest patch (2.3 ha) during the 31-year period from 1984 to 2014. Thirty-two contiguous patches of high severity fire were >10 ha, and all of these occurred during the six large wildfires of 2015, 2017, 2020, and 2021. The three largest contiguous patches of high severity fire were each >100 ha and collectively spanned 554.2 ha—more than 5% of giant sequoia’s native range.

Potentially beneficial fire (low or moderate severity) occurred on 5904 ha, over three times the amount of high severity area burned. The Undetected change class accounted for an additional 1356 ha, some portion of which included beneficial fire. Area burned by severity for individual wildfires and impacted groves can be found in the Supplementary Material (Table A2).

Q2a: large giant sequoia mortality

The model showed a strong fit to the calibration data, with binned field observations closely aligning with model-based predictions across the range of RdNBR values (Fig. 4). Visual assessments of model fit further support this, as predictive distributions closely tracked average observed mortality across the full range of RdNBR values (Supplementary Materials, Appendix C, Figs. C1, C2). This agreement suggests that the model effectively captures the nonlinear relationship between remotely sensed RdNBR burn severity and large giant sequoia mortality, providing a robust basis for ecological inference and scenario evaluation.

Combining our modeled probability of large giant sequoia mortality based on RdNBR values with the expected density of large giant sequoias (6.6867 ha^{-1}) across grove areas affected by fire, we estimated a cumulative loss of approximately 17.6% of all large giant sequoias since 1984 (90% credible interval: 16.4–18.8%), which corresponds to an estimated ~12,340 trees. This estimate is likely to be conservative, given that the majority of mortality assessments occurred only 1 year postfire (mean = 2 years postfire) (Table 2) and thus undoubtedly missed some delayed mortality (Shive et al. 2022). Nearly all of the mortality occurred since 2015, with the majority occurring during the large fire years of 2020 and 2021. During this time, Freeman Creek, Redwood Mountain, Mountain

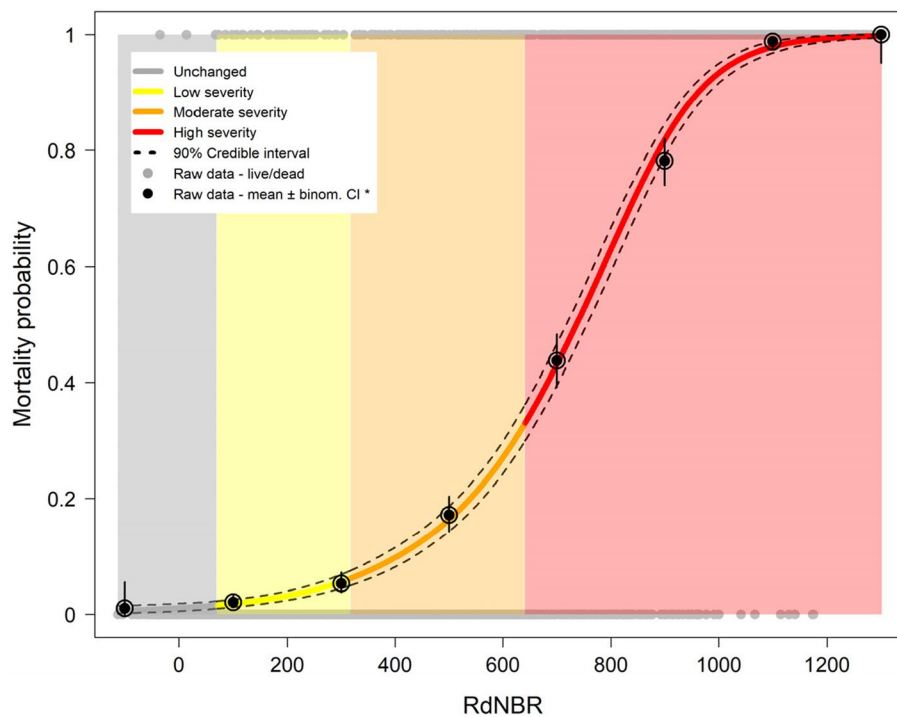


Fig. 4 Modeled probability (mean \pm 90% credible interval) of a large giant sequoia (> 107 cm DBH) dying from direct wildfire effects (i.e., dying within 1–5 years of the fire) as a function of remotely sensed burn severity metric “RdNBR” (Relativized differenced Normalized Burn Ratio; Miller & Thode 2007). *The proportion of live and dead sequoias (presented as 0 for live and 1 for dead) is presented as the mean \pm binomial 95% confidence intervals (Clopper and Pearson, 1934) from 200 RdNBR bins and plotted at the median of each bin. For example, the mean and standard error for the proportion of live vs. dead large sequoias within RdNBR values of 0–200 are plotted at RdNBR = 100

Home, and Wheel Meadow groves likely sustained the largest absolute losses of large giant sequoias, given the large areas burned at high severity within these groves (Supplementary Material, Appendix A, Table A1). In sharp contrast, between 1984 and 2014, only an estimated 0.2% of large giant sequoias were lost to wildfire (Fig. 5).

Q2b: local extirpation risk

Considering wildfires and treatment from 1984 to 2024, an estimated 13% of the range (1280 ha) is at risk of local extirpation due to limited expected natural regeneration and very low seed tree retention. Specifically, 3% (310 ha) was classified as very high risk and 5% (476 ha) was classified at high risk. Of these high and very high risk areas, 140 ha are in federally designated wilderness.

Q3: trends in treatment

A total of 9361 ha were recorded as treated during the 1951–2024 period (Fig. 6; note that the figure only shows 1969–2024 for readability), covering a footprint of 4788 ha (2609 ha of mechanical treatments, and 2903 ha of fire-related treatments). There has been an overall increasing trend in area treated since ~1995,

with stronger year-to-year increases in mechanical treatments since 2015 (Fig. 6). Maximum area treated by year and treatment type were mechanical treatments in 2023 (570 ha) and fire-related treatments in 2003 (480 ha). When comparing treatments from 1984 to 2024 with beneficial wildfire (low and moderate severity fire) during the same period, active management comprised 7949 ha, compared with 5905 ha of beneficial wildfire. Fire-related treatments alone covered 4464 ha, which is 76% of the total area impacted by beneficial wildfire. For large fire years in giant sequoia (2020 and 2021), active treatment comprised just 7% of the area burned by beneficial wildfire.

Treatments were not consistently tracked across agencies, but the three land managers that have conducted the most treatment (USFS, NPS, and MHDSF) also have the longest and most robust treatment records (Fig. 7). Considering activity hectares, we found different trends by managing agency. The USFS treated a total of 1648 ha with mechanical thinning between 1981 to 2024, with the maximum area treated in 2024 (261 ha). The USFS completed a total of 679 ha of fire-related treatment, with over half of this area being treated in 2024. The footprint of treated area covered 1393 ha, 34% of their grove area

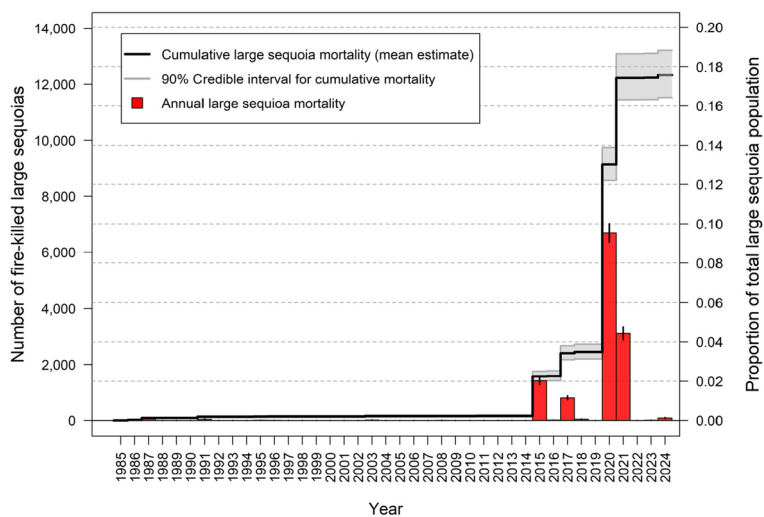


Fig. 5 Estimated fire-caused large giant sequoia mortality from 1985 to 2024. Presented are estimates of the number of large sequoias killed (left axis) and their corresponding proportion of the total large sequoia population (right axis), shown annually (bars) and cumulatively (lines) over time. Estimates are displayed as mean values with 90% credible intervals. See “Appendix B: Statistical Methods: model equation, coefficients, and priors” for details

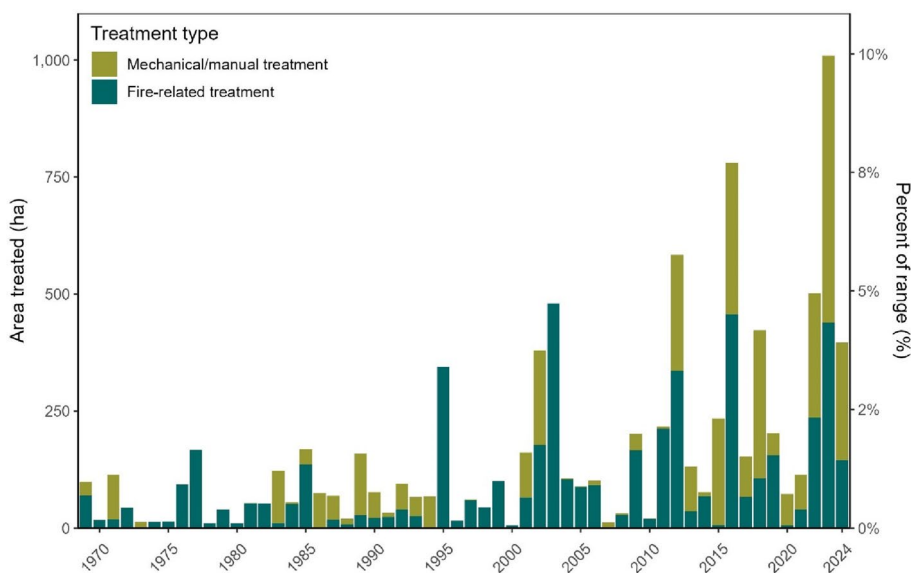


Fig. 6 Total annual treated area by the two coarse treatment classes in sequoia groves (left axis) and by the percentage of the giant sequoia range (right axis), 1969–2024. Note that prior to roughly 2010, some of the smaller giant sequoia land managers lack treatment records

(4158 ha), which included 1064 ha of mechanical treatment and 509 ha of fire-related treatments. On MHDSF lands, there was a total of 1079 ha of mechanical thinning, with 242 ha of fire-related treatments. Considering the footprint area treated, MHDSF treated 81% of their grove area (832 ha), which was dominated by mechanical treatments.

The NPS conducted the most treatment (activity hectares) in giant sequoia groves, totaling 4422 ha between 1970 and 2024 (Fig. 7). This is nearly twice that of the

USFS, which had the next highest treatment rates. The vast majority of treatments on NPS lands were fire-related treatments (3904 ha), most of which were broadcast burns, whereas most of the fire-related treatment on USFS lands was pile burning. The majority of NPS burns occurred in SEKI, which has much more giant sequoia area under their management than YOSE. A total of 518 ha were mechanically treated, with most of those being implemented more recently, including the largest annual area treated mechanically in 2024 (260 ha). For

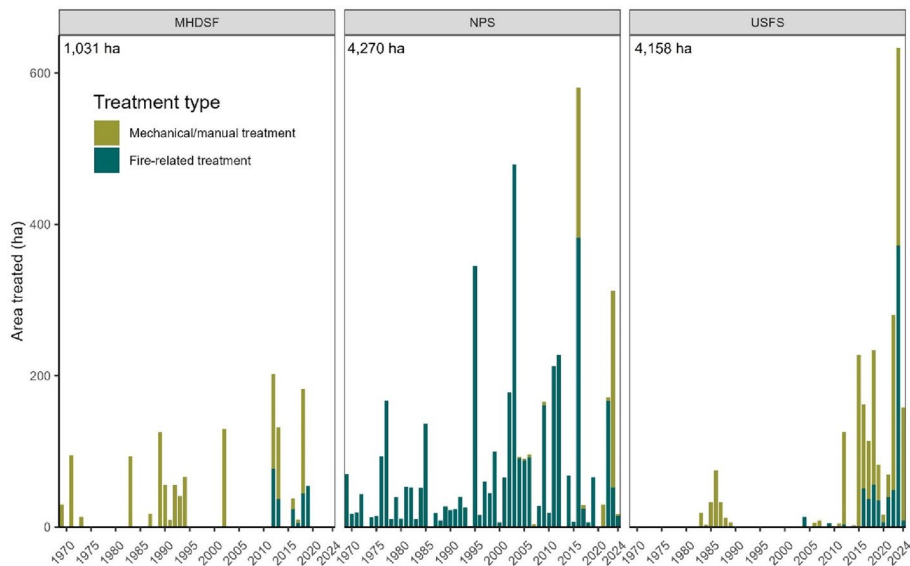


Fig. 7 Activity hectares for active management treatments for the three giant sequoia land managers that manage the largest area of giant sequoia, 1969–2024, since this is the period in which all three entities have treatment histories available. Note the total grove area managed by each agency is in the upper left

total area treated, the NPS treated 50% of their grove area (4270 ha).

For land managers with smaller areas of giant sequoia groves under their management, activity hectares treated between 1969 and 2024 included Calaveras Big Trees State Park (126 ha), UCB Whitaker’s Forest (141 ha), BLM Case Mountain (114 ha), and private/nonprofit landowners (265 ha). Management activities at Calaveras Big Trees State Park were primarily broadcast burning, whereas the other entities were dominated by mechanical treatments.

Q4: resistance to high severity fire

A snapshot of current resistance

We classified 26% of the range as High resistance (Fig. 8). Roughly 38% is classified as Moderate resistance, the vast majority of which is due to recent wildfire. Low resistance (mechanical treatments only) comprised 2%. Loss of mature giant sequoia forests due to high severity fire has occurred over 18% of the range (1840 ha), and 16% was classified as No resistance. Of the areas classified as having No or Low resistance (totaling 1824 ha) due to a

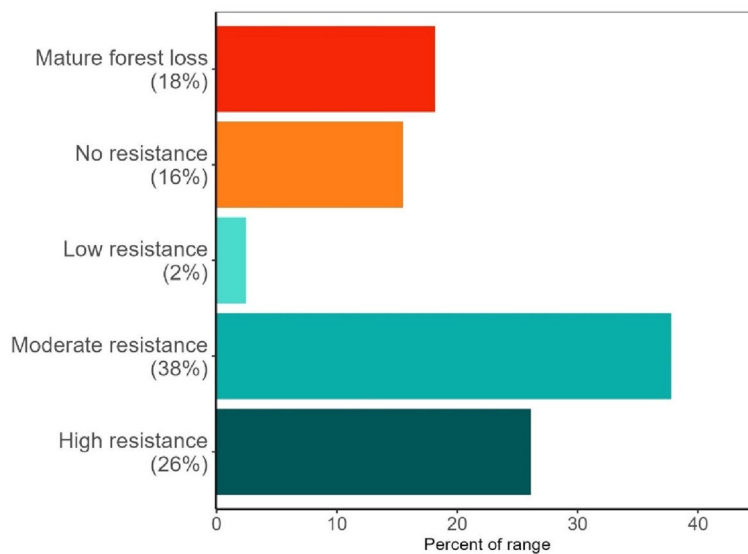


Fig. 8 Estimated relative resistance to high severity wildfire and mature forest loss across the giant sequoia range, based on disturbance history

lack of recent fire history, 686 ha were undetected change areas of wildfires, where a light underburn may have occurred. The distribution of resistance classes within individual groves can be found in the Supplementary Material (Table A3).

Tracking resistance through time

There are 686 ha that had some level of resistance before 2010, which has likely faded without retreatment (Fig. 9, dark shaded area). This included a total of 242 ha that would have been classified as High resistance and 376 ha that would have been classified as Moderate resistance. There are an additional 1177 ha that last had a beneficial disturbance in 2010–2015, which could lose their resistance if another treatment does not occur in roughly the next 5 years (Fig. 9, light shaded area). Over time, capitalizing on the Moderate resistance created by recent fires would require the most retreatment area with active management or beneficial wildfire.

Discussion

A decade of change

The last decade brought significant changes to the giant sequoia range, with the largest impacts driven by extensive high severity fire. The increase in area burned at high severity has been on the rise in historically frequent-fire forests throughout the western US, driven primarily by climate change and fuel accumulation (Abatzoglou

and Williams 2016; Parks et al. 2025). In giant sequoia, lengthy fire history records show that these extensive, severe fires are anomalous at millennial time scales (Stephenson et al. 2024a). In addition to the increase in total high severity area, we observed individual patches of high severity spanning hundreds of contiguous hectares, orders of magnitude larger than historical patch sizes that ranged from a few hundredths of a hectare to a few hectares (Stephenson 1996, 1999; Stephenson et al. 2024a).

These extensive areas of high severity are the largest contributor to our cumulative total mortality estimate of ~17.6% (90% credible interval of 16.4–18.8%) of large giant sequoia. Considering 2020 and 2021 fire seasons only, we estimate a total of 14% mortality, which is within the lower end of the initial estimates for these fire years that were generated with a coarser approach (13–19%; Shive et al. 2021; Stephenson and Brigham 2021). The use of continuous severity data and a larger calibration dataset, which also includes substantially greater spatial and temporal variation than the previous effort, likely improved the accuracy of our estimate. However, the estimate is still likely to be conservative, since the majority of trees were surveyed 1-year postfire and do not capture delayed mortality. Stephenson et al. (2024a, b) estimated that given the high fire frequencies preceding the era of fire exclusion, a typical 1000-year-old giant sequoia will have lived through more than 60 fires. That the recent extreme fire events are killing large swaths of

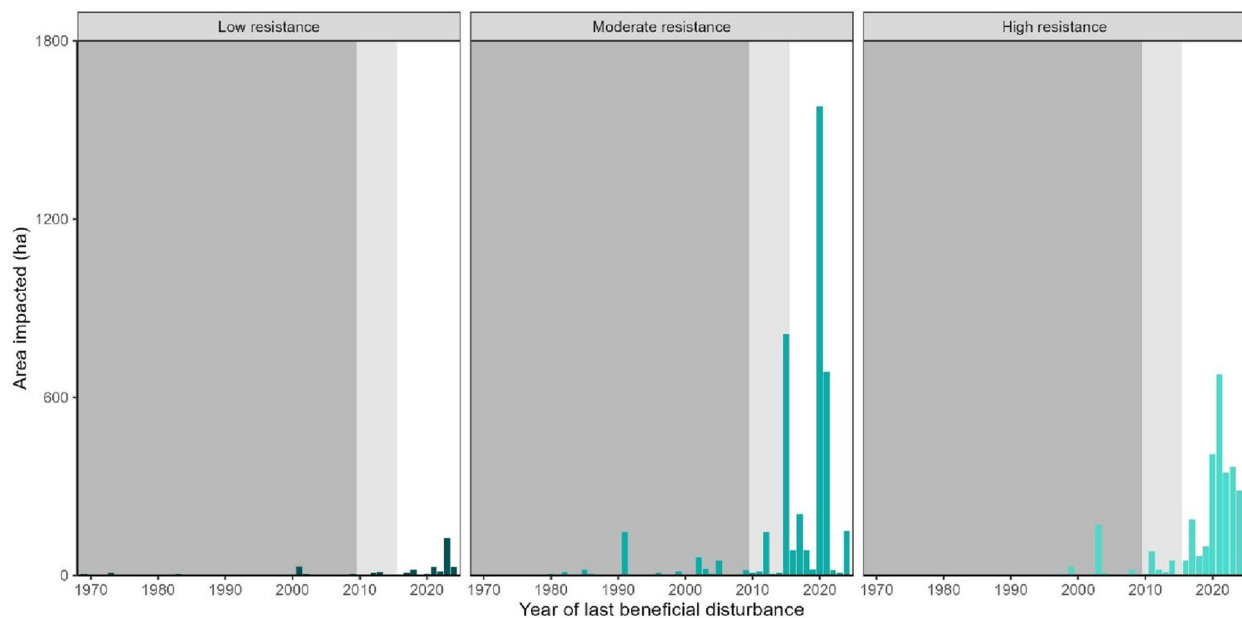


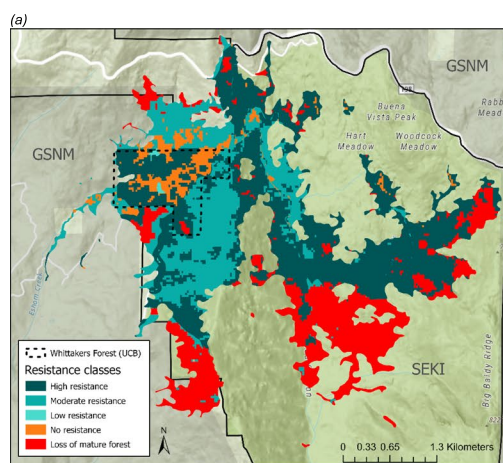
Fig. 9 Giant sequoia grove area by most recent resistance class and last treatment (1970–2024). Beneficial disturbances include fire-related treatments or low to moderate severity fire. The dark grey shaded area represents > 15 years after the last beneficial disturbance, where any resistance that was created has likely been lost. The light grey shaded area includes 2010–2015, highlighting where follow up treatments would likely need to happen soon to enhance or maintain resistance before fuels conditions are hazardous again

large and old giant sequoias highlights just how anomalous the modern fire regime is.

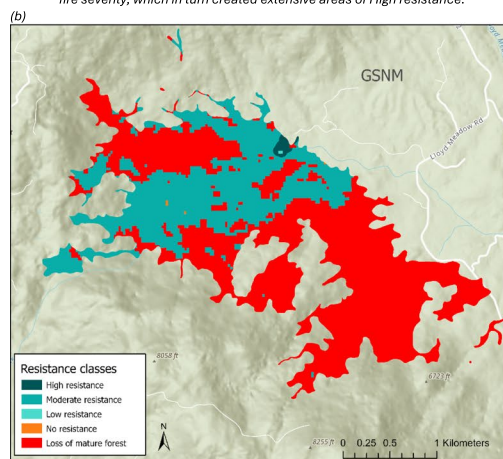
The loss of these highly culturally valued trees is also threatening the onsite persistence of giant sequoia in some areas. We estimated that a total of 13% of the range is at some risk of local extirpation, with 8% at high or very high risk as a result of the loss of seed trees and limited immediate postfire regeneration. This mirrors a well-documented issue in large patches of high severity in other historically frequent fire, dry conifer forests of the western US (Chambers et al. 2016; Kemp et al. 2019; Shive et al. 2018). However, this trend is particularly alarming given that giant sequoias are semi-serotinous. While successful giant sequoia regeneration is strongly linked to fire, the type of fire is important. Some areas of very low severity may not result in enough canopy gap creation and seed release that facilitates abundant postfire regeneration, but such areas were a normal part of the heterogeneous burning patterns in ancient fires (Stephenson et al. 2024a, b), and mature tree retention means that there are still future opportunities for regeneration. As fire severity increases, so does regeneration, but only to a point. The recent, novel occurrence of *very* high severity—areas that experienced crown fire with total crown consumption—is associated with very limited postfire regeneration and a lack of mature trees to contribute seeds into the future (Soderberg et al. 2024). As a result, forest managers are increasingly planting giant sequoia seedlings in some areas of high severity to ensure local giant sequoia persistence (National Park Service 2023; Sequoia National Forest and Giant Sequoia National Monument 2023a, b). Given the limited distribution of this highly valued species, some of these planting efforts have occurred in remote federally designated Wilderness areas, which adds significant logistical challenges since these areas do not have road access. Roughly 140 ha of the areas that we classified most at risk are within Wilderness (e.g., some areas of Mature forest loss in Redwood Mountain Grove, Fig. 10a). It is important to note that our inferences of extirpation risk depend on predicted relationships between remotely-sensed data, large tree survival, and regeneration (Soderberg et al. 2024; Soderberg and Das 2023), but there will of course be variation on the ground. While the risk areas we identified are likely the most concerning, managers may choose to plant in other areas depending on the actual conditions on the ground, and/or differing management objectives.

Treatment trends

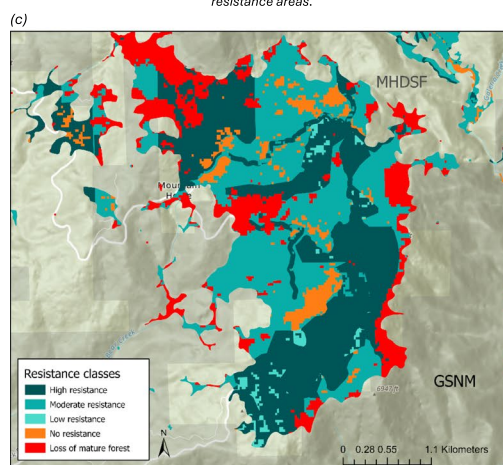
There is now ample research showing that, in historically frequent-fire forests, long-unburned stands with heavy woody fuel loads and high tree densities tend to burn more severely than areas that have had restoration



Redwood Mountain Grove. The NPS has planted sequoia seedlings in some areas of the grove with Mature forest loss. The history of prescribed fire (eight prescribed fires in and surrounding the upper grove between 2004-2016) likely contributed to reduced fire severity, which in turn created extensive areas of High resistance.



Freeman Creek Grove, Giant Sequoia National Monument (GSNM). The grove is dominated by areas of Mature forest loss after the 2020 Castle Fire, but still retains areas with live, large sequoias with Moderate resistance to high severity fire. GSNM is currently thinning and conducting pile burning treatments in portions of the Moderate resistance areas.



Mountain Home Grove, Mountain Home State Demonstration Forest (MHDSF) and GSNM. MHDSF had an extensive history of mechanical thinning treatments and some pile burning and prescribed fire. Many of these areas burned at lower severity in the 2020 Castle Fire, creating large areas of High resistance.

Fig. 10 Sequoia groves with varied resistance to high severity fire and different disturbance histories: **a** Redwood Mountain, **b** Freeman Creek, and **c** Mountain Home groves

to reduce fuels (Davis et al. 2024; Kalies and Yocom Kent 2016). The majority of giant sequoia groves were long unburned and untreated prior to recent wildfires, making the fuel conditions extremely hazardous and anomalous (Das et al. 2025; Parsons and DeBenedetti 1979; York et al. 2013). While statistical models specific to sequoia groves have not yet been published, anecdotal evidence shows that in at least one grove, Redwood Mountain, the areas of lower severity fire line up nearly identically with areas that had previously had prescribed fire, while the area with no past treatments burned at very high severity (Boerigter et al. 2024). These treatments also facilitated some backburning along the road during the wildfire to help reduce fire severity, which was safe to do in part because of the prior restoration activities (Hankin et al. 2023).

Overall, we found that the pace and scale of treatments in the giant sequoia range have been increasing in the last decade, particularly after the 2020 and 2021 fire seasons, but the trends differed slightly by managing agency and treatment type. Fire-related treatments fluctuated strongly through the entire period of record, which is likely due to shifting burn windows (Bajinath-Rodino et al. 2022; Swain et al. 2023), the alignment of burn windows with staff availability, and the status of environmental compliance (Schultz et al. 2019; Striplin et al. 2020; Swain et al. 2023). Reductions in fuels budgets in the 2010s (Riddle 2020) meant fewer staff to plan and implement prescribed burns or pile burns, and in recent years, large fires also interrupted planned burns.

Notably, fire-related treatments still comprised a larger proportion of treated area within giant sequoia groves than they do in the more widespread Sierra Nevada yellow pine and mixed conifer forest type (Shive et al. 2025), likely due to the concentration of groves in national parks, where broadcast burning is the primary forest management tool. This emphasis on prescribed fire resulted in a greater proportion of NPS grove area being in the High resistance category than USFS grove area, particularly when considering resistance that was conferred by active treatments only (i.e., without wildfire-induced resistance). Moreover, the NPS emphasis on broadcast burning rather than pile burning also likely contributes to more overall resistant conditions (Davis et al. 2024). However, NPS fire-related treatments have been heavily concentrated in a handful of accessible groves that have been prescribed burned in national parks since the 1970s (e.g., Giant Forest, General Grant Grove, Redwood Mountain Grove, Mariposa Grove). The emphasis on specific groves has paid off in that, outside of areas where wildfires created the High resistance, these areas of repeated treatments comprise much of the 26% of the range currently with High resistance to high

severity fire. Yet if expanding prescribed fire to include less accessible groves is desired, managers could consider the use of “potential operational delineations” (PODs; Thompson et al. 2016), which have been proposed as one way to facilitate landscape-scale prescribed fire. In addition, several studies have identified funding, staffing and policy changes that could be addressed to support increasing prescribed fire implementation (Clark et al. 2024; Schultz et al. 2019). Managed wildfire could also be used in more remote areas containing groves based on a PODs approach (North et al. 2024).

Mechanical treatments have also fluctuated but show a clearer increasing trend, likely due in part to the onset of severe wildfires in the range in 2015, with the NPS in particular using much more mechanical thinning after the 2020 fire season (National Park Service 2022; US Forest Service 2022). Mechanical treatments have been the primary management tool of the USFS, where most of the High resistance areas were created by wildfire intersecting mechanical treatments. There has been a substantial increase in area treated mechanically by the USFS since 2015, which is likely due in part to a relatively novel combination of the onset of extensive severe fire, emergency restoration funding (US Forest Service 2022), completion of the updated 2023 Sequoia National Forest Management Plan (US Forest Service 2023c), and partnerships with outside entities that have facilitated implementation (Giant Sequoia Lands Coalition 2024).

While the increase in mechanical treatments is important for achieving structural restoration goals that can also help confer resistance to drought and insect infestations (Fettig et al. 2022; Restaino et al. 2019), the additional application of fire is critical for reducing fire severity. Prescribed fire or thinning plus prescribed fire has repeatedly been shown to be more effective than thinning-only treatments in reducing fire severity (Davis et al. 2024; Kalies and Yocom Kent 2016). Combined thinning and prescribed fire may be more effective than prescribed fire alone in some cases (Brodie et al. 2024; Kalies and Yocom Kent 2016). Another benefit of using combined treatments is that they can more quickly move a stand toward target conditions than a single application of prescribed fire (Stephens et al. 2009); while multiple prescribed fires or lower severity wildfires can also help reach desired conditions (Jeronimo et al. 2019), this approach necessarily takes much longer because fuels must reaccumulate enough to facilitate subsequent burns. Where managers have identified an urgency to reduce fuels in the few remaining long-unburned groves (National Park Service 2022; US Forest Service 2022), thinning plus burning treatments could increase the resistance to high severity fire and other stressors more quickly than using fire-related treatments alone. On

the other hand, some managers might decide to use fire alone for their treatments, either because their groves are remote and not easily treated mechanically, or because they determine that—given the funds available to them—they can treat significantly more area with fire than they can mechanically, given the lower implementation costs for prescribed fire (Holland et al. 2022). Ultimately, deciding on the restoration approaches will involve weighing funding and resource availability, site access, and desired outcomes (fire resistance and/or other restoration goals).

Current conditions and opportunities

Despite the extensive losses of this highly valued species to severe fire, recent wildfires have also created opportunities. The extensive area of Moderate resistance (38% of the range) was created partly through prescribed fire but most is due to low and moderate severity wildfire. These areas are first-entry fires, where large trees survived to varying degrees and surface fuels were generally consumed (Das et al. 2025; Shive et al. 2022). Given the substantial evidence that multiple treatments are required to reach target conditions (Stephens et al. 2012; Davis et al. 2024), additional treatments could help enhance resistance to severe wildfires (i.e., shifting to High resistance), but the timing and type of treatments would vary depending on postfire condition. For example, in Moderate resistance areas, wildfire-killed trees will fall and increase woody fuel loads, and, in some areas, there may still be too many live trees relative to desired conditions. Treatments to enhance resistance could include mechanical treatments to remove some of the standing dead material or reduce live tree density soon after the fire, which could be pile burned or carried off site (see Fig. 2, Moderate resistance). Alternatively, managers could wait until the fine woody fuels reaccumulate enough to apply a broadcast burn.

While in the past forest managers have focused almost exclusively on high severity areas for postfire management, this is beginning to change. For example, the GSNM is working to enhance resistance by thinning and piling in grove areas that recently burned at lower severity (Sequoia National Forest and Giant Sequoia National Monument 2023a, b). The Freeman Creek Grove was prized as the largest unlogged grove outside of NPS lands prior to the 2020 Castle Fire, but it also had no recent fire or fuel treatments, yielding very high surface fuel loads and tree densities (Meyer et al. 2025; Sillett et al. 2019). Given those conditions, it is not surprising that the grove experienced extensive forest loss (Fig. 10b). In the Moderate resistance areas of Freeman Creek Grove (i.e., low to moderate severity), the postfire thin and pile-burn treatments are clearing dead trees and, in some cases,

reducing live tree density where it was still higher than desired conditions after the fire. These actions have the potential to move these areas into the High resistance condition. This work may be particularly important for Moderate resistance areas in a sea of Mature forest loss (Fig. 10b). High severity areas tend to regenerate with dense shrubs and the fire-killed trees eventually transition to elevated woody fuel loads, which often results in severe reburns (Steel et al. 2021; van Wagtenonk et al. 2012). This can potentially expand the initial high severity footprint into neighboring low to moderate severity burned areas. GSNM is also applying similar postfire treatments to Long Meadow, Packsaddle, and other groves.

Another opportunity to enhance resistance could be to burn out unburned islands where the surrounding fuels were consumed. For example, Redwood Mountain and Mountain Home groves (Fig. 10a, c) each have pockets of No resistance, which in these cases are areas of “undetected change” within a larger wildfire burned area. While other management considerations will need to come into play, including how these areas contribute to fuels heterogeneity across the landscape, these areas could be prescribed burned shortly after the wildfire with reduced implementation complexity. Because the surface fuels in the surrounding burned forest have been largely removed (Das et al. 2025), the labor needs for constructing control lines can be substantially reduced. However, these opportunities are ephemeral since fuels will reaccumulate (van Wagtenonk and Moore 2010), highlighting the importance of being able to act fast. One experienced burn boss estimated that the window to be able to burn these areas with minimal preparation to be roughly 3 years postfire (Ben Jacobs, Environmental Scientist and Burn Boss, Calaveras Big Trees State Park, personal communication, June 13th, 2025). Completing the necessary planning and environmental compliance to implement a burn within this timeframe could be challenging in many cases (Clark et al. 2024; Morgan et al. 2021; Schultz et al. 2019). This situation has prompted calls for shifting policy on the required compliance for prescribed fire (Clark et al. 2024).

Between 1984 and 2024, the amount of potentially beneficial wildfire (low and moderate severity) was 32% greater than the area treated with fire-related treatments (e.g., prescribed fire or pile burning), highlighting that these fires can create substantial benefits and opportunities. Notably, the gap between fire-related treatments and beneficial wildfire is much lower in giant sequoia groves than in the broader Sierra Nevada mixed conifer forest matrix which dominates the Sierra Nevada. In the ~2.2 million hectares of mixed conifer forests, Shive et al. (2025) found that beneficial wildfire has impacted over

four times more area than fire-related treatments over a slightly narrower time period (2001–2022). That beneficial wildfire in giant sequoia groves is only 32% higher than fire-related treatments is due primarily to the extensive work that the NPS has done to reintroduce fire into groves. The relative lack of wildfire in groves until 2015 also plays a role in this difference.

Recent wildfires also contributed to creating more High resistance areas, where wildfire overlapped with prior treatments or previous beneficial wildfires. For example, in Redwood Mountain Grove, the large areas of High resistance were created where low to moderate severity wildfire overlapped eight different prescribed fires that occurred between 2004 and 2016 (Fig. 10a). Other places like MHDSF were managed primarily with mechanical thinning, much of it including sustainable timber harvest; with the addition of a lower severity wildfire, much of the area now has High resistance (Fig. 10c).

Where capacity is limited, there could be competing demands between working in long-unburned forests, recently burned areas and eventually, implementing maintenance treatments in high resistance areas. Increasing the use of managed wildfire or landscape-scale prescribed fire has the potential to help overcome some of those capacity limitations (North et al. 2024). Moreover, we hypothesize that once a stand has met target conditions, there is a longer window than there would be after a first entry treatment until it becomes hazardous again. This could apply to some of the areas of “fading resistance” (e.g., grey areas of Fig. 10), which our framework classified as No resistance because more than 15 years had passed since the last treatment.

To take advantage of these wildfire-created opportunities, additional research would help us better understand fuel reaccumulation rates across differing severities, disturbance histories, and site conditions. With so much giant sequoia grove area burned in recent years, forest managers could benefit from more information on these patterns to inform priorities around retreatments, since capacity restraints means that follow-up treatments may need to be staggered through time.

Study limitations

The primary limitation of our analyses is the presence of errors in, or inadequate resolution of, the spatial data. While we worked directly with forest managers to confirm treatment areas, there are likely some errors in the exact spatial configurations on the ground (Knight et al. 2022). To facilitate a range-wide analysis, we also made generalized assumptions about the impact of treatments and wildfire, but the actual results on the ground can vary considerably. For example, a prescribed fire in one area

may have been successful at meeting restoration goals, but in another area may have burned too cool to meet objectives, in which case our classification of resistance could be an overestimate. In addition, the low and moderate severity classes that we considered to be beneficial fire necessarily include a wide range of conditions, some which may not be considered restorative on the ground (e.g., the very low end of low severity that may fail to sufficiently reduce elevated fuels or the very high end of moderate severity that may kill more large giant sequoias than is desirable). In addition, while repeated fire is often restorative (Collins et al. 2016; Jeronimo et al. 2019), the starting conditions matter. A recent study found that in degraded (e.g., second or third growth) forests, some areas that burned twice at low or moderate severity burned at high severity in a third fire, because of the extensive dead biomass remaining on site (Jasperse et al. 2025). Because the majority of the giant sequoia range is in an old-growth condition, this may be less of a concern, but it reiterates the importance of local conditions, and that inferred conditions from disturbance history will need to be confirmed on the ground. Given these points, our resistance analysis is likely best suited to understanding range-wide patterns and for general overviews of individual groves, but a more detailed look would be needed for future management planning (Meyer et al. 2021). Finally, our focus here is on giant sequoia and does not consider the impacts to co-occurring tree species within giant sequoia groves. While we expect wildfire and treatment effects on these species to be largely similar, regeneration of the non-giant sequoia conifers is likely to be very different from giant sequoias, since none of them are serotinous. After high severity fire, regeneration of these other conifers is likely to be limited by distance to live tree seed source alone (Davis et al. 2023; Shive et al. 2018).

Conclusions

Our assessment focused on the condition of the giant sequoia range as of early 2025, based on shifts in fire regimes. We documented significant impacts on large giant sequoia survival and potential risks to long-term species persistence in parts of its current geographic range. We also highlighted opportunities to work with the more positive outcomes of wildfire. However, a full understanding of the “state of the giant sequoias” requires a better grasp of other novel climate-related stressors to the species, about which we know little. For example, the extensive 2012–2016 drought resulted in foliage die-back in some stands, but the areas most impacted were not where prior analyses had predicted the species to be most at risk (Stephenson et al. 2018).

In addition, the interacting stressors of drought and fire appear to be contributing to some of the first observations of giant sequoia mortality linked with attack by bark beetles (*Phloeosinus punctatus*; Foote et al. 2024). Researchers are just beginning to understand the basic biology of these beetles and the extent of their impact. It is also unclear where and when a warming climate may influence patterns of giant sequoia regeneration and the potential for high severity reburns (e.g., Steel et al. 2021). In short, a more robust understanding of direct and indirect climate stressors will be critical for a comprehensive understanding of the “state of the giant sequoias.” Nonetheless, the snapshot provided here can help guide forest management in a time of rapidly changing fire regimes.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s42408-026-00469-5>.

Supplementary Material 1. Includes Appendix A: Supplementary tables and figure; Appendix B: Additional methodological details: spatial data; and Appendix C: Additional methodological details: mortality estimates.

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Authors' contributions

K.S. Conceptualized the paper. K.S., B.B. and D.S. compiled the datasets and did the analysis. K.S., B.B. and D.S. prepared the figures. K.S. and D.S. prepared the tables. L.H., D.S., A.D., M.M., B.N. and S.B. contributed data. K.S. wrote the manuscript text with revisions from all authors.

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Data availability

Data and code are available on request, and may eventually be uploaded to Dryad.

Declarations

Ethics approval and consent to participate

Not applicable.

Competing interests

The authors declare no competing interests.

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