Received: 24 February 2023 | Revised: 20 June 2023 | Accepted: 3 October 2023

DOI: 10.1002/eap.2932

ECOLOGICAL APPLICATIONS
ECOLOGICAL SOCIETY OF AMERICA

ARTICLE

Special Feature: Long-term ecological effects of forest fuel and restoration treatments

Forest restoration and fuels reduction work: Different pathways for achieving success in the Sierra Nevada

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Funding information
The US Joint Fire Sciences Program

Handling Editor: Carolyn Hull Sieg

Abstract

Fire suppression and past selective logging of large trees have fundamentally changed frequent-fire-adapted forests in California. The culmination of these changes produced forests that are vulnerable to catastrophic change by wildfire, drought, and bark beetles, with climate change exacerbating this vulnerability. Management options available to address this problem include mechanical treatments (Mech), prescribed fire (Fire), or combinations of these treatments (Mech + Fire). We quantify changes in forest structure and composition, fuel accumulation, modeled fire behavior, intertree competition, and economics from a 20-year forest restoration study in the northern Sierra Nevada. All three active treatments (Fire, Mech, Mech + Fire) produced forest conditions that were much more resistant to wildfire than the untreated control. The treatments that included prescribed fire (Fire, Mech + Fire) produced the lowest surface and duff fuel loads and the lowest modeled wildfire hazards. Mech produced low fire hazards beginning 7 years after the initial treatment and Mech + Fire had lower tree growth than controls. The only treatment that produced intertree competition somewhat similar to historical California mixed-conifer forests was Mech + Fire, indicating that stands under this treatment would likely be more resilient to enhanced forest stressors. While Fire reduced modeled wildfire hazard and reintroduced a fundamental ecosystem process, it was done at a net cost to the landowner. Using Mech that included mastication and restoration thinning resulted in positive revenues and was also relatively strong as an investment in reducing modeled wildfire hazard. The Mech + Fire treatment represents a compromise between the desire to sustain financial feasibility and the desire to reintroduce fire. One key component to long-term forest conservation will be continued treatments to maintain or improve the conditions from forest restoration. Many Indigenous people speak of "active stewardship" as one of the key principles in land management

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and this aligns well with the need for increased restoration in western US forests. If we do not use the knowledge from 20+ years of forest research and the much longer tradition of Indigenous cultural practices and knowledge, frequent-fire forests will continue to be degraded and lost.

KEYWORDS
carbon, climate change, mixed conifer, prescribed fire, resilience, restoration thinning, wildfire

INTRODUCTION

Fire exclusion and suppression have fundamentally changed frequent-fire-adapted forests (historic fire return interval <35 years) in California by increasing tree densities and fuel loads (Minnich et al., 1995; Safford & Stevens, 2017; Stephens et al., 2015). Selective logging of large trees has also impacted California's forests by opening up space for mostly shade-tolerant species to regenerate and by removing the most fire-resistant trees (Agee & Skinner, 2005; Collins et al., 2017). The culmination of these changes has produced forests that are vulnerable to catastrophic change by wildfire, drought, and bark beetles with climate change making existing conditions even more vulnerable (Hagmann et al., 2021; Stephens et al., 2022).

Active management that modifies forest structure and fuel loads (including shrubs) is necessary to reduce these vulnerabilities. Frequent-fire forests can be treated to reduce their fire hazards by mechanical treatments (thinning and/or mastication), prescribed fire, or combinations of these treatments. One recent paper that summarized 56 studies addressing fuel treatment effectiveness from eight western US states found general agreement that thinning followed by prescribed fire had positive effects in terms of reducing fire severity, tree mortality, and crown scorch (Kalies & Kent, 2016). In contrast, burning or thinning alone had either lesser or no effects, compared with untreated controls. A recent study found that prescribed fire and forest thinning were critical in preventing high-severity wildfires from impacting the Mariposa giant sequoia (*Sequoiadendron giganteum*) grove in Yosemite National Park (Hankin et al., 2023) further adding to the literature of the effectiveness of fuel treatments.

A long-term study that manipulated the forest density of a Sierra Nevada old-growth mixed-conifer forest using prescribed burning and thinning 12 years prior to the severe 2012–2016 drought produced some interesting results (Steel et al., 2021). All mixed-conifer species had neutral to reduced mortality rates following thinning alone, but treatments that included prescribed fire increased bark beetle infestation rates and increased the mortality of red fir (*Abies magnifica*) and large sugar pines (*Pinus lambertiana*). Fuel reduction treatments benefited some species such as Jeffrey pine (*Pinus jeffreyi*) but reduced the resistance to extreme drought and bark beetle outbreaks in other species when treatments include prescribed burning (Steel et al., 2021).

Despite increasing fire suppression efforts, both the total area burned and high-severity area burned in the western US have increased as temperatures and widespread drought accelerated near the end of the 20th century (Abatzoglou & Williams, 2016; Parks & Abatzoglou, 2020; Westerling et al., 2006). An eight-fold increase in annual area burned by high-severity fire occurred between 1985 and 2017 in western US forests (Parks & Abatzoglou, 2020), and fuels have been implicated as the primary driver of stand replacing fire in most regions (Parks et al., 2018; Steel et al., 2015). In California forests the top 1% of fires by size from 1985 to 2020 accounted for the majority (58%) of high-severity fire effects and this threatens long-term forest conservation (Cova et al., 2023). This highlights the need for increased use of forest restoration and fuel treatments to reverse these trends (Hagmann et al., 2021; Stephens, Battaglia, et al., 2021). We also need better information on the finances of various fuel reduction treatments because managers will inevitably have to address this factor as they consider the trade-offs associated with selecting different treatment alternatives (Hartsough et al., 2008).

Implementing treatments at scales sufficient to alter contemporary disturbance regimes and recover other ecosystem functions associated with low- and moderate-severity fires will involve rapidly increasing rates of forest management (Hessburg et al., 2021; North et al., 2012; Spies et al., 2006). Managers in the western US have implemented forest restoration and fuel treatments with research done simultaneously to study their ecological impacts (Covington et al., 1997; North et al., 2007; Stephens et al., 2012). While a great deal of information exists on the immediate effects (<3 years) of forest restoration and fuel treatments, as of 2016, only two studies have measured the differences between treated and untreated sites >10 years post treatment (Kalies & Kent, 2016). This highlights the need for longer term studies on this important topic.

The objectives of this study were to investigate the long-term results from a robust, replicated study on fuels and forest restoration treatments in the northern Sierra Nevada. We quantify fuel accumulation, vegetation change, potential fire behavior, intertree competition, and economics across multiple treatments. Further, we elucidate what appears to be distinct pathways in fuel development among four different treatment regimes: multiple applications of prescribed fire (Fire), multiple mechanical restoration thinnings (Mech), multiple mechanical restoration thinnings followed by prescribed fire (Mech + Fire), and untreated controls (Cont). This study includes one of the longest running investigations in the western US on fuel reduction and forest restoration and should be of interest to managers and scientists who are working to restore frequent-fire forests to be more resilient to wildfire, drought, and climate change.

METHODS

Study area

This study was performed at the University of California Blodgett Forest Research Station (Blodgett Forest), approximately 20 km east of Georgetown, California. Blodgett Forest is located in the mixed-conifer zone of the northern Sierra Nevada at latitude 38°54′45″ N, longitude 120°39′27″, between 1100 and 1410 m above sea level, and encompasses an area of 1780 ha. Tree species in this area include sugar pine, ponderosa pine (*Pinus ponderosa*), white fir (*Abies concolor*), incense-cedar (*Calocedrus decurrens*), Douglas-fir (*Pseudotsuga menziesii*), and California black oak (*Quercus kelloggii*). Soils at Blodgett Forest are well developed, well drained Haploxeralfs (Alfisols) derived from either andesitic mudflow or granitic/granodiorite parent materials (Moghaddas & Stephens, 2007). Slopes across Blodgett Forest averaged less than 30%.

The climate at Blodgett Forest is Mediterranean with a summer drought period that extends into the fall. Winter and spring receive the majority of precipitation which averages 160 cm (Stephens & Collins, 2004). Average temperatures in January range between 0 and 8°C. Summer months are mild with average August temperatures between 10 and 29°C, with infrequent summer precipitation from thunderstorms. Fire was common in the mixed-conifer forests of Blodgett Forest before the policy of fire suppression and exclusion began early in the 20th century. Between 1750 and 1900, median composite fire intervals at the 9–15 ha spatial scale were 4.7 years with a fire interval range of 4–28 years (Stephens & Collins, 2004). Forested areas at Blodgett Forest have been repeatedly harvested and subjected to fire exclusion and suppression for the last 120 years reflecting a management history common to many forests in California and elsewhere in the western US (Graham et al., 2004).

Forest restoration treatments

The primary objective of the national Fire and Fire Surrogate Study (FFS) was to modify stand structure such that 80% of the dominant and co-dominant trees in the post-treatment stand would survive a wildfire modeled under 80th percentile weather conditions (McIver et al., 2012). The secondary objective was to create a stand structure that maintained or restored several forest attributes and processes including, but not limited to, snag and coarse woody debris, floral and faunal species diversity, nutrient cycling, and seedling establishment. To meet these objectives at Blodgett Forest four different treatments (1) Mech, (2) Mech + Fire, (3) Fire, and (4) untreated controls (Cont) (Figure 1) were each randomly applied (complete randomized design) to 3 of 12 experimental units that varied in size from 14 to 29 ha. The total area for the 12 experimental units is 225 ha. To reduce edge effects from adjoining areas, data collection was restricted to a 10 ha core area in the center of each experimental unit (Stephens & Moghaddas, 2005).

Cont units received no treatment during the study period. Mech treatment units had a two-stage prescription; in 2001 stands were crown thinned followed by thinning from below to maximize crown spacing while retaining 28–34 m^2 ha^{-1} of basal area with the goal of producing an even species mix of residual conifers (Stephens & Moghaddas, 2005) focusing on what trees to leave after treatment versus what could be harvested (restoration thinning). Individual trees were cut using a chainsaw and yarded with ground-based skidding. All residual trees were well spaced with little overlap of live crowns in dominant and co-dominant trees. Following the harvest, approximately 90% of understory conifers and hardwoods up to 25 cm diameter at breast height (dbh) were masticated in place using an excavator-mounted rotary masticator and this material was not removed from the experimental units. A second Mech treatment was done with understory mastication in 2017 followed by a second thinning from below in 2019. Mech + Fire units underwent the same initial treatment as Mech units, but in addition, were prescribed burned using a backing fire in the fall of

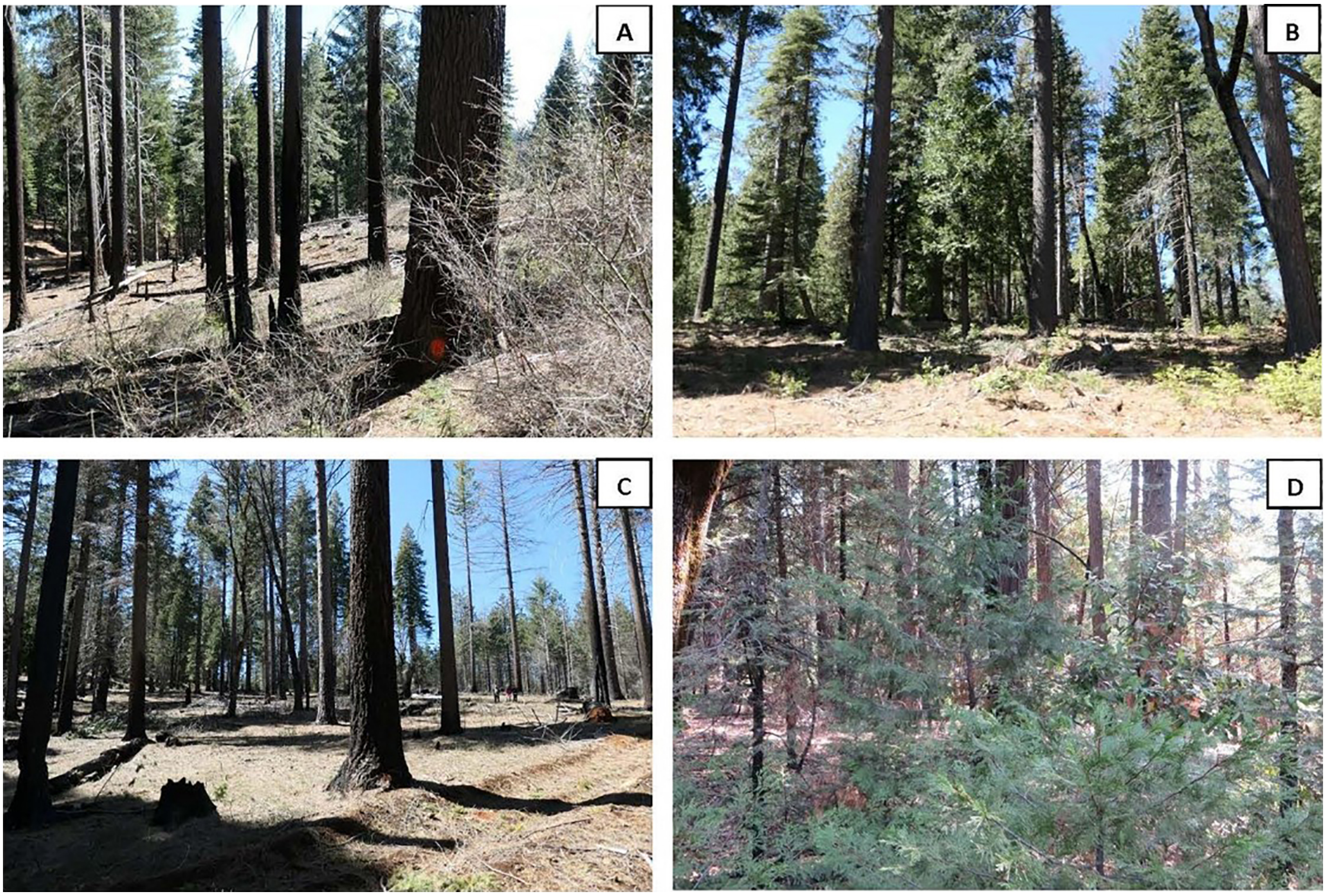

FIGURE 1 Photograph panel of the four fuel and restoration treatments at Blodgett Forest in the northern Sierra Nevada in 2022. (A): Fire; (B): Mech; (C): Mech + Fire; (D): Control. Photographs taken by Scott Stephens.

2002. In 2017 these units were masticated a second time (similar to mechanical only), but not thinned, and burned with a backing fire in 2018. After this second fire salvage harvesting of clumps of dead trees occurred in 2019 in the Mech + Fire units. Fire units were burned with no pretreatment using strip head fires in the fall of 2002, 2009, and 2017. Prescribed fire prescription parameters for temperature, relative humidity, and wind speed were 0–10°C, >35%, and 0.0–5 km h^{-1}, respectively. The desired 10-h fuel stick moisture content was 7%–10%.

Vegetation measurements

Overstory and understory vegetation was measured with 20, 0.04-ha, circular plots, measured in each of the experimental units in 2001 (PRE), 2003 (POST-1YR), 2009 (POST-7YR), 2014 (POST-12YR), and 2020 (POST-18YR). Individual plots were placed on a systematic 60-m grid with a random starting point. Plot centers were permanently marked with a pipe and by tagging witness trees to facilitate plot relocation after treatments. Tree species, dbh, total height, height to live crown base, and crown position (dominant, co-dominant, intermediate, suppressed) were recorded for all trees greater than 15 cm dbh. Canopy cover was measured using a 25-point grid in each 0.04 ha plot with a site tube. Understory and shrub species were identified in a 0.04 ha subplot using an ocular cover estimate and average height (in centimeters) estimate.

Fuel measurements

Surface and ground fuels were sampled with two random azimuth transects at each of the 240 plots using the line-intercept method (Brown, 1974) on the same schedule as the vegetation measurements. In total, 480 fuel transects were installed and the same azimuths were used during remeasurements. The 1-h (0–0.64 cm) and 10-h (0.64–2.54 cm) fuels were sampled from 0 to 2 m, 100 h (2.54–7.62 cm) fuels from 0 to 3 m, and 1000 h (>7.62 cm) and larger fuels from 0 to 11.3 m on each transect. Duff and litter depth (in centimeters) were measured at 0.3 and 0.9 m on each transect. Surface and ground fuel loads were calculated using appropriate equations developed for California forests (Foster, 2018).

Relative stand density index

For all treatments, we calculated each plot's current (2020) stand density index (SDI) which is a common forest management metric that indicates stocking levels and it can be used to measure intertree competition as done in North et al. (2021). We used a theoretical maximum value of SDI that was estimated by Long and Shaw (2012) describing mesic-mixed-conifer forests (1359 trees per hectare; 550 trees ac^{-1}) to calculate relative SDI (% of maximum SDI). This theoretical maximum was chosen based on the high productivity present at our study site. Based on relative SDI, we assigned competition "zones" to each plot using benchmarks (Long, 1985; Long & Shaw, 2005) that indicate it is "free" from competition (≤25% of maximum SDI), under partial competition (25%–35%), full site occupancy (35%–60%), or within the "zone of imminent mortality" that is driven by density-dependent competition (≥60%).

Fire modeling

We modeled fire behavior for each inventory plot for two time periods, 2001 (pretreatment) and 2020, with the Fire and Fuels Extension (FFE) of the Forest Vegetation Simulator (Reinhardt & Crookston, 2003). FFE uses established equations to predict fire behavior and crown fire potential based on user-input tree lists and fire weather (Reinhardt & Crookston, 2003). Weather for each simulation was under "severe" conditions defined by FFE as a windspeed of 32 km h^{-1}, temperature of 21°C, 1-h fuel moisture of 3%, 10-h fuel moisture of 4%, 100-h fuel moisture of 5%, 1000-h fuel moisture of 10%, duff fuel moisture of 15%, and live (woody and herb) fuel moisture of 70%.

We used Scott and Burgan (2005) to assign fuel models for each plot during both time periods (2001, 2020). These fuel model assignments were based on both measured plot fuel loads for each time period and observed fuel bed characteristics in the field. As recommended by Scott and Burgan (2005), we first determined which type of surface fuels were most likely to carry fire (Appendix S1: Figure S1). Similar to FFE, we estimated the fraction of biomass that was herb and shrub relative to the amount of total fuel biomass (i.e., the sum of herb, shrub, and fine woody fuels [1-h, 10-h, and 100-h fuels]) for each plot and used breakpoints to delineate fire-carrying fuel types. Allometric equations were used to convert the percent cover of shrubs (McGinnis et al., 2010), herbs, and grasses (Muukkonen et al., 2006) to biomass (gram per square meter). To avoid an undefined ratio, plots without any shrubs were assigned 0.00001 g m^{-2} for shrub biomass. We then determined which fuel model—within the respective fire-carrying fuel type—had the closest fine woody fuel and shrub load estimates to our observed values. This was done by treating fine woody fuel and shrub load estimates as Cartesian coordinates and using the following formula to calculate the distance between fuel model estimates and observed values:

$$\text{distance} = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2},$$

where X_1 is the fuel model biomass of fine woody fuels, X_2 is the observed biomass of fine woody fuels, Y_1 is the fuel model biomass of shrubs, and Y_2 is the observed biomass of shrubs. The fuel model with the closest distance to the observed values was chosen as our fuel model. We also chose an additional fuel model based on the amount of ground fuels (litter and duff) and coarse woody fuels (≥1000-h fuels) in each plot. Ground and coarse woody fuels for each plot were categorized as "low" (<25th percentile of observations), "moderate" (25th–75th percentile), and "high" (>75th percentile). Using the assigned fire-carrying fuel type for each plot, we chose fuel models with potential fire behavior that we believed were representative of the ground and coarse woody fuel classes. If a given plot was characterized by the same two fuel models, we did not assign an additional fuel model. Before simulating fire behavior in FFE, plots with two assigned fuel models had each model weighted using the inverse of the distance from the fuel model to the observed conditions:

$$\text{Weight FM}_i = \frac{\frac{1}{\text{distance}_{\text{FM}_i}}}{\sum_{i=1}^{2} \frac{1}{\text{distance}_{\text{FM}_i}}}.$$

Fire behavior outputs that we obtained from FFE for each plot during both time periods were probability of torching (P-torch) and potential mortality (P-mort; Rebain, 2015) which were derived using a weighted average from the assigned fuel models (Foster et al., 2020; Stephens et al., 2009). The advantages of P-torch over other more conventional modeled fire behavior output are: (1) simple and intuitive interpretation; (2) it does not rely on the calculation of canopy base height, which can be problematic because it can exhibit strong thresholds that do not reflect actual changes in stand conditions (Rebain, 2015); (3) it is a continuous variable, which avoids some of the error associated with categorical measures of hazard, for example, fire type; and (4) it integrates several stand-level contributors of fire hazard (surface fire flame length and intensity, tree density, and tree heights) into a single metric, making it ideal for informing fuel treatment planning (Rebain, 2015). For each plot, we used the predicted P-mort to discount the live tree carbon stock (estimated using regional biomass equations) to estimate the stock of stable live tree carbon (the amount of carbon in live trees predicted to survive a wildfire) as described in Foster et al. (2020).

Data analysis

We used a series of (generalized) linear mixed-effects models to evaluate the effects of the treatments on several plot-level characteristics. The characteristics (and response variable distribution for each) were: net change in basal area from 2003 to 2020 (Gaussian), number of large trees at least 76.2 cm dbh on a plot in 2001 and 2020 (Poisson), number of snags at least 30.5 cm dbh on a plot in 2001 and 2020 (Negative Binomial), relative SDI in 2020 (Gaussian), canopy cover in 2020 (Beta), (log) surface fuel loads in 2020 (Gaussian), duff fuel loads in 2020 (Tweedie), P-torch in 2020 (Beta), and stable live tree carbon in 2020 (Gaussian). Response variable distributions were determined iteratively. Initial models were fitted defaulting to a Gaussian distribution for continuous data, a Poisson distribution for count data, or a Beta distribution for proportion data. If the initial models failed validation tests (described below), models were iterated (e.g., using a Tweedie distribution instead of a Gaussian for nonnegative continuous duff loads or by log-transforming the surface fuel loads) until they passed validation tests. Model results were only examined for the final models (Appendix S1: Table S1). Every model included a fixed effect of treatment and a random effect of the experimental unit on the mean parameter, with hypothesis tests determining whether the control effect was significantly different from 0 and whether each treatment was significantly different from the control. The models for net change in basal area, relative SDI, canopy cover, duff load, and stable live tree carbon also included a fixed effect of treatment on the dispersion parameter, allowing within-experimental-unit heterogeneity to vary by treatment. The model for the P-torch included zero inflation with a fixed effect of treatment on the probability of a plot having a P-torch of 0. Treatment effects on dispersion parameters and zero inflation were necessary for some models to pass the validation tests implemented in the *DHARMa* package for R (Hartig, 2021). Models passed all validation tests, except for the net change in basal area model failing the outlier test but linear mixed effects models are generally robust to such minor violations of assumptions (Schielzeth et al., 2020). For each model, we interpret effects using a significance threshold determined using a Bonferroni correction applied to a significance level of 0.05, with each model serving as the family for determining the number of comparisons.

Treatment costs and revenues

The objective of this analysis is to provide stand-level costs and revenues over the entire study period, in order to identify possible differences in economic sustainability among treatment alternatives. Costs and revenues for mechanical treatments are from Blodgett Forest monitoring data and receipts from sawmills. Mastication costs were determined by tracking equipment hours and hectares treated. Hourly rates for fuel, operator, and depreciation costs were applied to provide dollar-per-hectare costs. Per hectare timber harvest costs, including cutting, yarding, and delivering of sawlogs, were acquired directly from the lowest contract-operator bids and from maps of areas harvested. Revenues came from bids of sawmills, which purchased delivered sawlogs. Prescribed fire costs were calculated from Blodgett Forest records, which track labor and supplies associated with planning, burn area preparation, burning operations, and post-burn patrol. Because Cont had no costs or revenue, it was not included.

The economic return of treatments in terms of accomplishing reductions in wildfire hazard was assessed with two metrics that were output from the fire modeling described above. First, we calculated the cost of decreasing P-torch by dividing the net cost per hectare by the overall change in P-torch across the 20 years (i.e., cost of reducing P-torch by one percentage point). This metric emphasizes the value of altering fire behavior. Second, to emphasize the value of treatments in reducing timber loss we calculated the cost of protecting the basal area from wildfire-related mortality. This was calculated similarly as above, but instead of P-torch, we used the overall change in basal area mortality predicted from wildfire (i.e., cost of protecting 1 m^2 ha^{-1}).

RESULTS

Basal area

The mean (standard deviation) net change in basal area from 2003 to 2020 in the control was 0.69 (0.63) m^2 ha^{-1} $year^{-1}$ (Figure 2). The net change was lower on Mech plots at 0.24 (0.61) m^2 ha^{-1} $year^{-1}$ and on Fire plots at 0.15 (0.75) m^2 ha^{-1} $year^{-1}$, but these were not significantly different from controls (Figure 2). The net change in Mech + Fire plots was significantly lower than Cont plots at −0.35 (1.08) m^2 ha^{-1} $year^{-1}$. Mech + Fire plots also had significantly higher within-unit variation in basal area change than did controls.

Density of large trees

There was a mean (standard deviation) density of 18.0 (23.0) large trees (stems >76.2 cm dbh) per hectare on the Cont plots in 2001. The mean density of large trees in 2001 was not significantly different from Cont for the Mech at 19.4 (18.7) stems per hectare, Fire at 14.2 (17.3) stems per hectare, or Mech + Fire at 25.6 (24.9) stems per hectare. The mean density of large trees increased to 38.6 (32.5) stems per hectare on the Cont by 2020, a change that was statistically significant (Figure 3). Fire plots accumulated large trees slightly faster than the Cont stands while the Mech and Mech + Fire plots accumulated large trees slower than Cont plots, resulting in 2020 densities of 35.8 (25.8) for Mech, 33.1 (27.2) for Fire, and 25.6 (21.4) for the Mech + Fire units. The Mech + Fire plots accumulated large trees at a significantly lower rate than the controls.

Density of snags

The mean (standard deviation) snag density in 2001 was 12.1 (17.7) stems per hectare on Cont plots, and was not significantly different on Mech at 15.5 (21.5) stems per hectare, Fire at 8.4 (18.7) stems per hectare, or Mech + Fire at 12.3 (19.0) stems per hectare. Snag density on Cont plots increased to 25.6 (34.6) by 2020, although this change was not statistically significant. The change in snag density in 2020 was not significantly different between any treatment and the controls, with the Mech falling to 10.7 (19.3) stems per hectare, Fire increasing to 17.6 (21.5) stems per hectare, and the Mech + Fire increasing to 19.5 (26.4) stems per hectare.

Canopy cover

The mean (standard deviation) canopy cover was 76.9% (15.0) in 2020 for control units. Canopy cover was lower, but not significantly so, on both Mech at 58.8% (18.4) and the Fire units at 59.0% (18.5). Canopy cover was significantly lower than Cont on Mech + Fire unit at

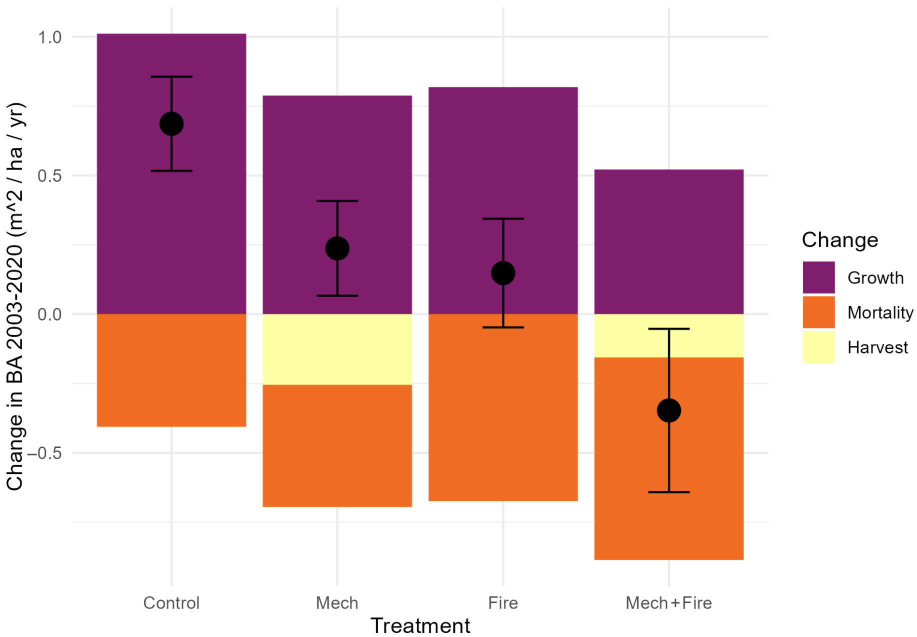

FIGURE 2 Gains, losses, and net change in basal area from 2003 to 2020. For each treatment, bars indicate the plot-level mean annualized accumulation of basal area in live trees (purple), basal area losses to mortality (orange), and basal area losses to harvests (yellow). Mean plot-level net change in live basal area for each treatment is shown as black points, with error bars showing ± two standard errors.

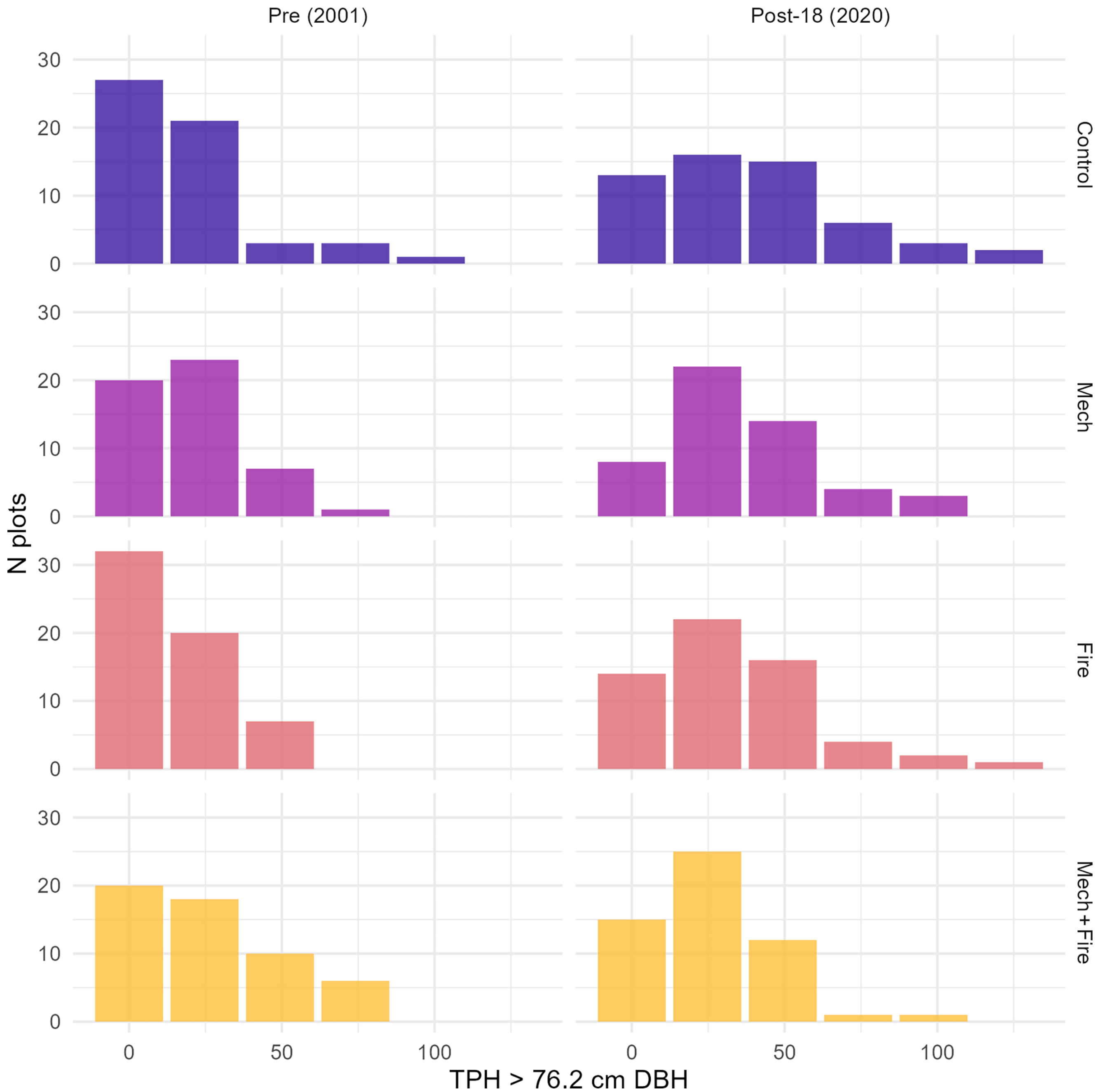

FIGURE 3 Density of large trees (live stems more than 76.2 cm diameter at breast height) in 2001 and in 2020. Panel columns correspond to the year and panel rows correspond to the treatment. In each panel, a histogram shows the number of plots (*y*-axis) with a given density of live trees (*x*-axis).

37.0% (20.6). There was no evidence that any treatment significantly affected the dispersion parameter (controlling heterogeneity across plots within a unit).

Surface fuels

The mean (standard deviation) surface fuel load on control units was 84.9 (60.5) Mg ha^{-1}. Surface fuel loads in Mech were lower at 69.9 (52.2) Mg ha^{-1}, although the difference with Cont was not significant (Figure 4). Surface fuel loads on Fire and Mech + Fire treatments were significantly lower than Cont, at 49.0 (41.4) Mg ha^{-1} and 32.2 (25.6) Mg ha^{-1}, respectively.

Duff load

The mean (standard deviation) duff load on control plots was 61.7 (38.3) Mg ha^{-1}. Duff loads were lower in the

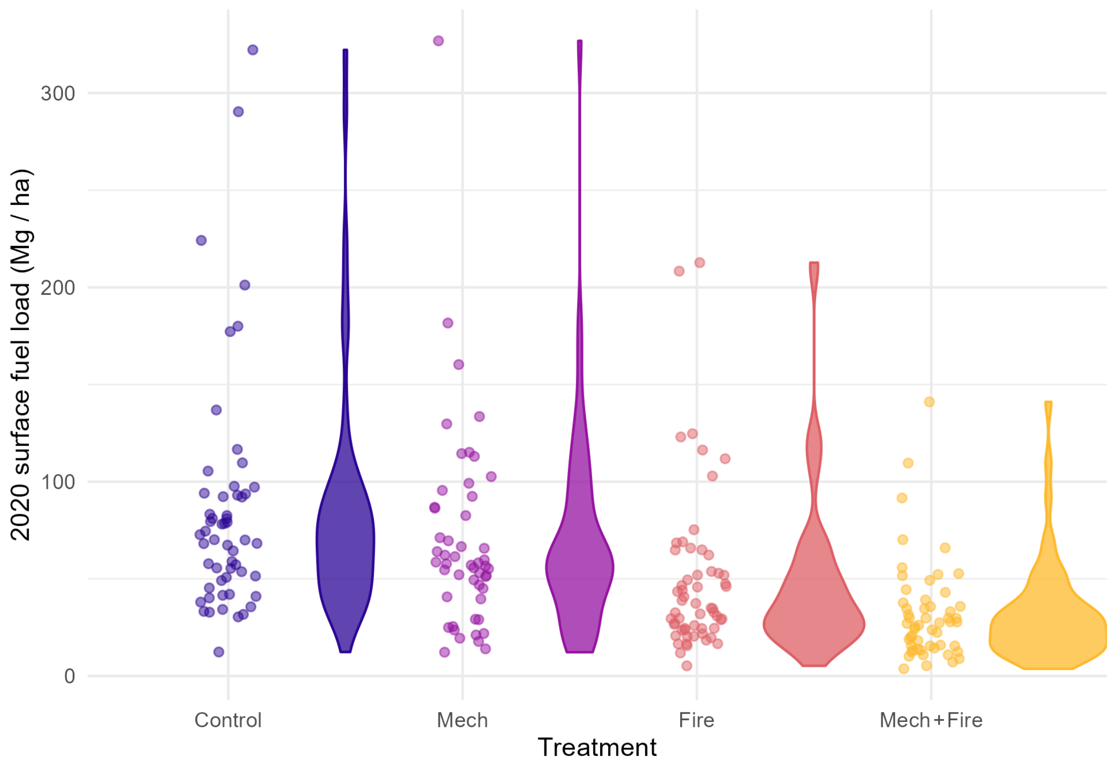

FIGURE 4 Current (2020) distribution of surface fuel loads (including litter, fine woody debris, coarse woody debris). Points are shown for each plot, with treatment on the *x*-axis and observed surface fuel load on the *y*-axis. Violin plots show the overall distribution of surface fuel loads within each treatment.

Mech at 51.0 (37.7) Mg ha^{-1}, but this difference was not statistically significant compared with controls (Figure 5). On the Fire and Mech + Fire units, duff loads were significantly lower than controls at 11.1 (11.2) and 13.8 (25.1) Mg ha^{-1}, respectively. Within-unit heterogeneity in duff loads was significantly higher in the Mech + Fire than in the controls.

Relative stand density index

The mean (standard deviation) relative SDI in 2020 was 75.4 (20.7) on controls. Relative SDI in 2020 was significantly lower than Cont in all active treatments, at 43.8 (15.3) for Mech, 51.1 (16.9) for Fire, and 33.8 (14.4) for Mech + Fire (Table 1, Figure 6). Mech + Fire had significantly less within-unit heterogeneity in relative SDI than did controls.

P-torch

The modeled P-torch was equal to 0 on 12.7% of Cont, 39.2% of Mech, 55.9% of Fire, and 87.0% of Mech + Fire units. Plots from all three active treatments had a significantly higher probability of having zero P-torch than Cont. Of plots where P-torch was greater than 0, the mean (standard deviation) P-torch was 0.75 (0.34) in Cont, 0.36 (0.36) in Mech, 0.56 (0.36) in Fire, and 0.16 (0.15) in Mech + Fire. Both Mech and Mech + Fire had significantly lower levels of P-torch on plots where P-torch was greater than 0.

Stable live tree carbon

The mean (standard deviation) stable live tree carbon in 2020 on control units was 114 (126) Mg C ha^{-1}. All three active treatments had higher mean stable live tree carbon than Con: Mech 145 (76) Mg C ha^{-1}, Fire 152 (78) Mg C ha^{-1}, and Mech + Fire 119 (66) Mg C ha^{-1}. However, no treatment had a significant effect on stable live tree carbon relative to the controls (Figure 7). All three active treatments had statistically significant effects on the dispersion parameter, each reducing the variance across plots within a unit relative to the controls.

Treatment costs and revenues

Fire had a net cost (US\$163 ha^{-1} year^{-1}; Table 2), with the cost of prescribed fires declining with each

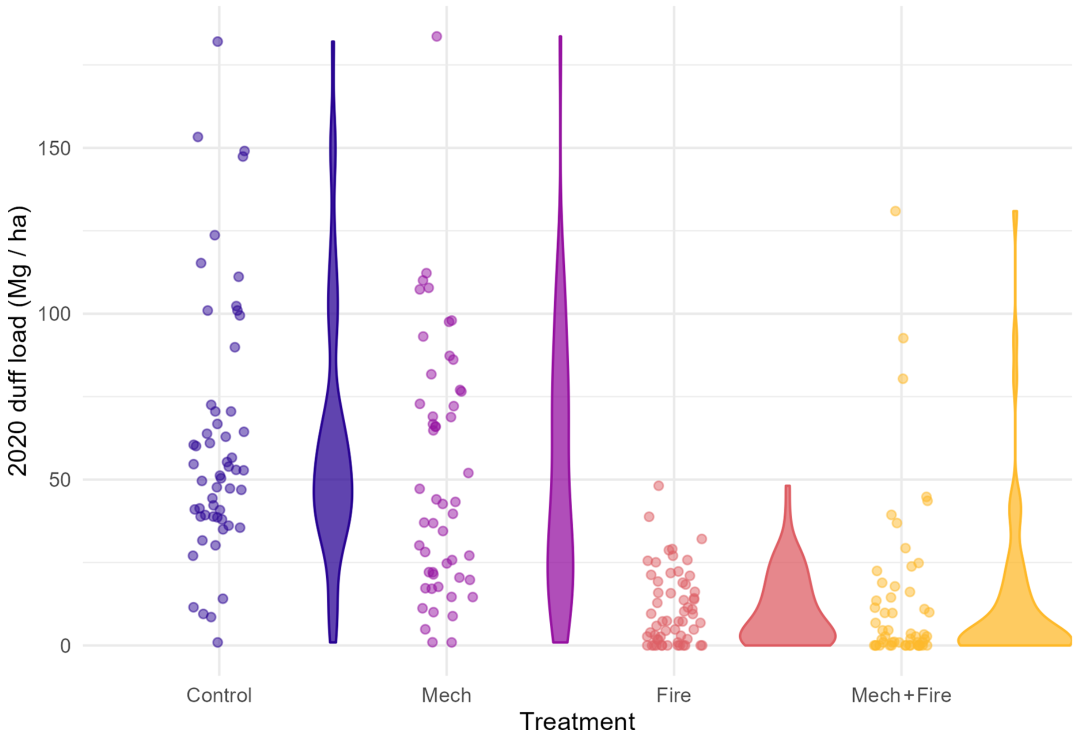

FIGURE 5 Current (2020) distribution of duff loads. Points are shown for each plot, with treatment on the *x*-axis and observed duff load on the *y*-axis. Violin plots show the overall distribution of duff loads within each treatment.

TABLE 1 Current (2020) relative SDI (% of SDI_{max}) conditions across treatments including mean, interquartile range, coefficient of variation, and percentage of observations in each treatment that fall within each competitive benchmark (free, partial, full, and imminent mortality [IM]).

Relative SDI	Control	Fire	Mech	Mech + Fire
Mean (range)	75% (59–94)	51% (41–60)	44% (31–56)	34% (21–46)
Coefficient of variation	28%	33%	35%	43%
Free (≤25% SDI_{max})	0%	5%	8%	27%
Partial (25%–35% SDI_{max})	0%	9%	21%	24%
Full (35%–60% SDI_{max})	27%	59%	53%	47%
IM (≥60% SDI_{max})	73%	27%	18%	2%

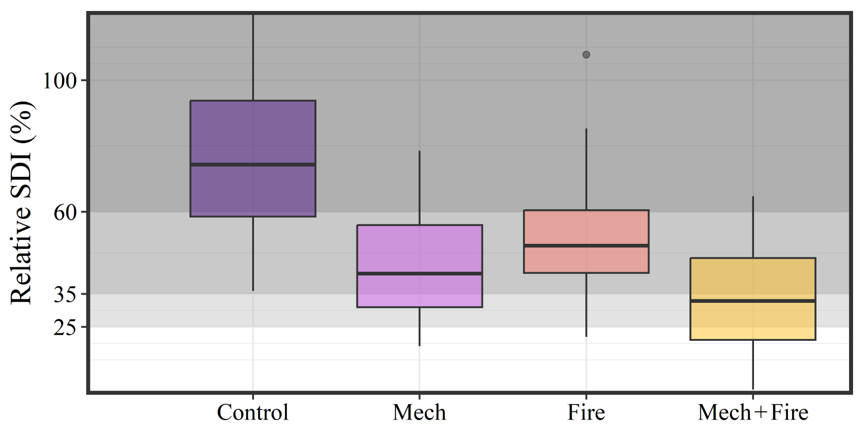

FIGURE 6 Current (2020) distribution of relative stand density index (% of maximum stand density index [SDI]) across treatments. The gradient of gray shaded boxes indicates SDI benchmarks for free competition (in white; <25%), partial competition (25%–34%), full site occupancy (35%–60%), and imminent mortality (≥60%).

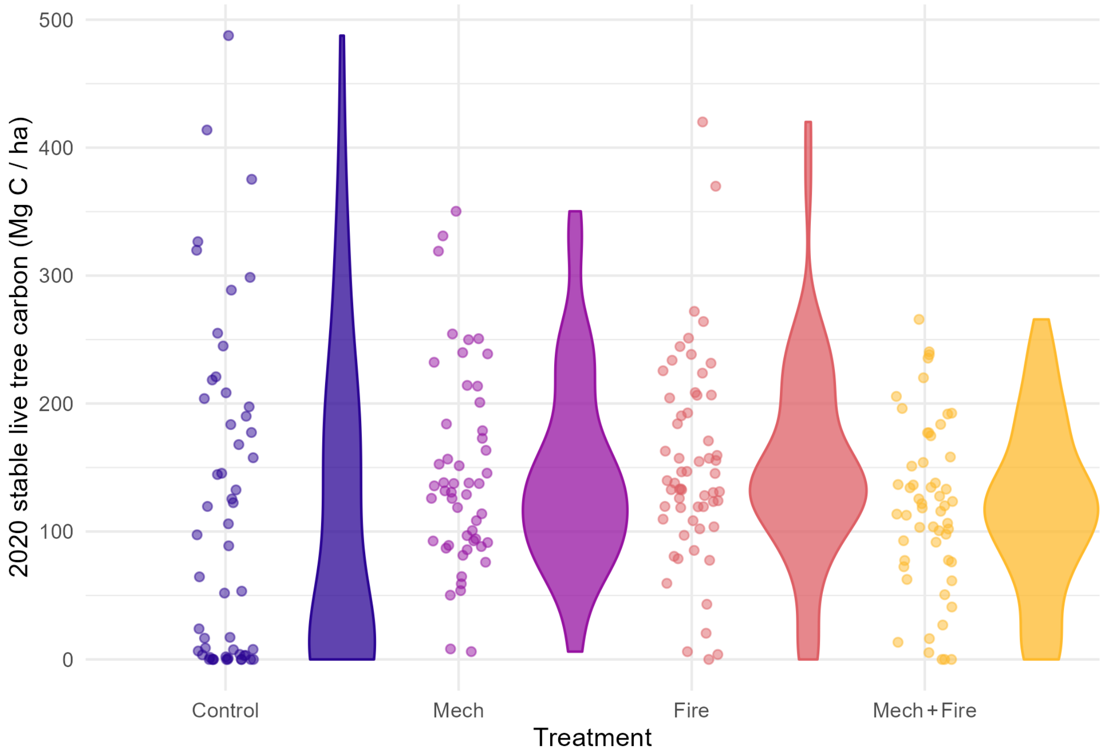

FIGURE 7 Current (2020) distribution of stable live tree carbon (live tree carbon expected to survive a modeled wildfire). Points are shown for each plot, with treatment on the *x*-axis and observed stock of stable live tree carbon on the *y*-axis. Violin plots show the overall distribution of stable live tree carbon stocks within each treatment.

subsequent entry. Mech + Fire was close to break-even in terms of cost, generating a small net revenue of US \$13 ha^{-1} year^{-1}. Mech generated revenues of US \$337 ha^{-1} year^{-1}. Each percentage point in P-torch reduction accomplished by Fire over the study period cost US\$11 ha^{-1} (Table 3). Mech generated a revenue of US\$16 ha^{-1} for each percentage point reduction, and Mech + Fire broke even at less than US\$1 revenue generated. Protecting 1 m^2 of basal area with Fire came at a cost of US\$67 ha^{-1}, Mech generated a revenue of US \$156 ha^{-1}, and Mech + Fire generated US\$7 ha^{-1}.

DISCUSSION

All three active fuel treatments produced forest conditions at the end of 20 years that were much more resistant to wildfire than the controls, demonstrating that there are different pathways for achieving success in Sierra Nevada mixed-conifer forests. The treatments that included prescribed fire (Fire, Mech + Fire) produced the lowest surface (Figure 4) and duff fuel loads (Figure 5) and the lowest wildfire hazards. Mech alone produced low wildfire hazards beginning 7 years after the initial treatment (most masticated fuels had decomposed) and Mech + Fire had lower tree growth when compared to Cont (Figure 2) because of fire damage to residual trees from initial-entry prescribed fires. That all active treatments improved wildfire hazards is great news to California forest managers and policymakers because there is so much restoration work to be done (Hessburg et al., 2021; North et al., 2012). From 1985 to 2021 there was a 6.7% decrease in forest cover across California mainly due to fire and drought (Wang et al., 2022) and fire losses were concentrated in large, continuous patches (Cova et al., 2023; Stevens et al., 2017) highlighting the need for increased restoration to conserve these forests. While federal planning frameworks such as the National Environmental Planning Act can slow down project implementation it is still critical to get the necessary work done in these forests.

Important wildlife habitat is being negatively impacted by forest loss (Jones et al., 2016; Stephens et al., 2016). In the southern Sierra Nevada, 30% of the region's conifer forest extent transitioned to nonforest vegetation from 2011 to 2020 due to severe fires and drought/bark beetle attacks (Steel et al., 2023). Fifty percent of mature forest habitats and 85% of high-density mature forests associated with late seral wildlife species either transitioned to lower density forest or nonforest vegetation types from 2011 to 2020. This further highlights the need to increase the pace and scale of forest restoration treatments in Sierra Nevada forests and elsewhere in the western US.

TABLE 2 Costs and revenues of the Fire and Fire Surrogate treatments examined at UC Blodgett Forest.

Treatment type	Rx fire cost (US$/ha)	Mast cost (US$/ha)	Harvest cost (US$/ha)	Revenue (US$/ha)	Net cost (US$/ha)
1st Treatment					
Fire	1210			0	1210
Mech	936		1633	5439	−2870
Mech + Fire	1210	936	1633	5439	−1660
2nd Treatment					
Fire	926			0	926
Mech		1482	3518	8193	−3192
Mech + Fire	790	1482	897	1737	1432
3rd Treatment					
Fire	790	0	790		790
Mech					
Mech + Fire					
All treatments				Net cost US$/ha	Net cost US$/ha/year
Fire				2927	163
Mech				−6062	−337
Mech + Fire				−228	−13

Note: TX: treatment.

TABLE 3 Costs of reducing fire severity over a 20-year period studied in the Fire and Fire Surrogate treatments examined at UC Blodgett Forest.

Treatment type	P-torch net change (% points)	US$ per point change	Bmort net change (% points)	US$ per point change	US$ per m^2 ha^{-1} protected
Fire only	−15	11	−31	5	67
Mech only	−20	−16	−26	−13	−156
Mech + Fire	−36	−0.4	−39	−0.3	−7
Control	26	0	5	0	0

Treatment intensity, defined as the amount and size of live trees killed or removed from a site, is an important consideration when designing restoration programs. Reducing surface and ladder fuels without changing overstory tree structure will improve resistance to wildfire (Agee & Skinner, 2005; Stephens et al., 2009) but may still leave forests vulnerable to drought and bark beetle attack (Steel et al., 2021) and may not regenerate shade-intolerant species sufficiently (Moghaddas et al., 2008). Even without exogenic disturbances such as drought, high residual stocking following treatments will increase fuel load recovery rates, leading to the need for more frequent treatments (York et al., 2021). Defining resilient forest conditions is challenging but a tool originally intended for timber management (Reineke, 1933) can be used to broadly assess the extent to which stands may be susceptible to higher levels of mortality (e.g., North et al., 2021). When this technique was applied to the Blodgett Forest treatments we saw that an overwhelming majority of the Cont plots were in the imminent mortality zone, while Fire plots are almost entirely in the full site occupancy zone, Mech plots are mostly in full site occupancy with a portion in the partial competition zone, and the Mech + Fire plots are mostly in partial competition with some areas in the Free Competition and full site occupancy zones (Figure 6). It should be noted that these categories are coarse evaluations of susceptibility to mortality within the context of timber management (i.e., it is beneficial to thin periodically in order to avoid high levels of mortality that may represent a loss of timber yield). When applied to restoration contexts, the value of an SDI approach comes from the ability to express stocking in terms relative to maximum thresholds that consider both site-specific productivity and tree size.

Ideally, managers would have long-term data sets to establish maximum thresholds, but empirical data needed for this are rare (Harmon & Pabst, 2015). Thus our interpretation of the SDI results is not necessarily that high mortality is immediately "imminent" in the control plots, but rather that they are more susceptible to mortality, especially during episodic exogenic events such as drought or bark beetle attacks.

Previous work found that the impacts of restoration treatments can have legacy effects. For some species, having experienced a prescribed burn more than a decade prior to drought increased the likelihood of beetle infestation and the probability of mortality (Steel et al., 2021), this effect was especially strong for large sugar pines. Another study in central Sierra Nevada mixed-conifer forests found that tree mortality during the 2012–2015 drought was substantially reduced by thinning done in 2011 (thinning reduced the overall mortality rate between 2014 and 2018 from 34% to 11%) (Knapp et al., 2021) demonstrating that treatments can increase forest resilience. Departures from vegetation patterns produced by active fire regimes (Stephens, Thompson, et al., 2021) have left many western US forests vulnerable to increased mortality from drought and fire, especially under a warming climate (Allen et al., 2015; Bryant et al., 2019; Hagmann et al., 2021; Keane et al., 2018) further highlighting the need to increase the pace and scale of restoration treatments (Hessburg et al., 2021).

Interestingly, we detected no net change in basal area from 2003 to 2020 in the Cont, Fire, and Mech treatments. The fact that Cont and Fire were similar is not nearly as surprising as the Mech being similar. This indicates that despite fairly substantial removals in the Mech restoration harvest there was enough basal area growth to more than compensate for the trees removed. The use of prescribed fire has resulted in minor to no long-term negative effects on tree growth in many studies (Busse et al., 2000; Peterson et al., 1994; Scherer et al., 2016) but burning prescriptions in these studies were probably mild as is the case in most projects in the western US. In contrast to Knapp et al. (2021), our Mech + Fire treatment reduced the net change in basal area versus controls. Even though the Mech treatment used the same silvicultural prescription as in Mech + Fire, the addition of backing fires with flame lengths of approximately 1 m killed some trees with bark beetles killing more trees a few years later (Stark et al., 2013). However this additional mortality produced a competitive environment for the remaining trees that should be better than the other treatments in this study (Figure 6).

Our findings that no active treatment had a significant effect on stable live tree carbon relative to controls warrants further discussion. Clearly the level of predicted canopy torching was greatest in the Cont, intermediate in the Mech and Fire treatments, and lowest in the Mech + Fire treatment. But these predictions were offset by tree removals, and in the case of the Mech + Fire, reduced growth associated with prescribed fire. It is worth noting that the Rothermel-based fire behavior predictions, including those from FFE, fail to capture extreme fire behavior observed in large wildfires (Stephens et al., 2022) and underrepresent actual proportions of high-severity effects (Collins et al., 2013). This leads to an underprediction of fire behavior, hence predicted tree mortality, that is likely more pronounced in untreated controls (Foster et al., 2020). Empirical evidence from recent large fire events in this forest type demonstrated that high tree densities and large concentrations of dead and downed fuel were strongly associated with high-severity fire effects (Safford et al., 2022; Stephens et al., 2022). Furthermore, when considering that higher density forests are exposed to elevated drought-related tree mortality, long untreated forests (similar to those in the controls) have an even greater risk of live carbon loss (Steel et al., 2023). When wildfire risk and offsite forest products are included in the analysis, Mech is the active treatment that maximized total carbon stocks (Foster et al., 2020), although we acknowledge our wildfire modeling may underestimate C losses, particularly in controls. More work is needed to develop fire behavior models that operate in extreme conditions to address this problem (Stephens et al., 2022).

The treatment costs and revenues analysis revealed distinct trade-offs among treatment approaches. While using prescribed fires (Fire) reduced predicted wildfire hazard and reintroduced a fundamental ecosystem process, it was done at a net cost to the landowner. Because continuing with a fire-only approach requires continual funding, it requires either long-term financial commitments (such as what fire suppression has had for >100 years) or subsidies that come from adjacent stands that incorporate forest product revenue. Using Mech that included mastication as well as restoration thinning resulted in positive revenues and was also relatively strong as an investment in reducing wildfire hazard (Mech made US$156 for each square meter per hectare protected while Fire cost US$67; Tables 2 and 3). Notably, the harvest removals were done within a sustained yield framework, meaning that removals were balanced with growth over the study period. Future revenue can therefore be expected to pay for maintenance treatments at Blodgett Forest, as long as sawmills purchase sawlogs at a rate that covers costs. The Mech + Fire treatments may represent a compromise between the desire to sustain financial feasibility and the desire to reintroduce fire. It was near break-even when considering its net cost to the landowner, and was also near break-even as an investment in reducing wildfire severity (Tables 2 and 3). The net cost of using the Mech + Fire approach may be positive or negative, given fluctuations in timber markets and planning costs. Merging timber and prescribed fire programs can be done in various ways that may be mutually beneficial to both economic and ecological objectives (York et al., 2022) and this deserves more study.

CONCLUSION

More than a century of fire exclusion and early selective logging that focused on large trees has produced mixed-conifer forests with high fire hazards (Hagmann et al., 2021; North et al., 2012; Safford & Stevens, 2017; Stephens et al., 2009; Stephens, Hall, et al., 2023). When this increase in live and dead vegetation is coupled with increased seasonal warming, it can produce prime conditions for large-scale forest loss (Cova et al., 2023; Parks & Abatzoglou, 2020; Parks et al., 2018; Steel et al., 2015, 2023). The remaining frequent-fire mature forest habitat in California may be susceptible to complete loss in the coming decades without a rapid transition from a conservation paradigm that attempts to maintain static conditions to one that manages for sustainable disturbance dynamics (Steel et al., 2023) and forest restoration and fuel treatments will be a key component to this strategy.

The most relevant result for managers from this 20-year study is that all three active treatments (Mech, Fire, Mech + Fire) produced conditions much more resistant to wildfire than the controls, demonstrating there are multiple operational pathways for achieving fuel reduction success in mixed-conifer forests. This is an important long-term result because different landowners have unique internal capacities to conduct different types of treatments. For example, a fire-only approach is feasible even in stands that have very high fuel loads and very high tree densities. Stands in the Fire treatment increased in basal area (Figure 2) while decreasing in surface fuel (Figure 4) over the study period, and the initial prescribed fire that was done during high fuel load conditions was low severity. This was indicated by no detectable change to canopy cover following the first fires (Stephens & Moghaddas, 2005). However, a fire-only approach requires both advanced technical resources as well as flexibility in conducting fires during seasonal windows when both fuel conditions and weather conditions allow safe burning. While larger agencies with fire-fighting resources (i.e., US Forest Service) are capable of utilizing this fire-only approach, smaller landowners or communities with smaller fire management capacities are more likely to use approaches similar to the Mech and Mech + Fire approaches. Creating forests more resilient to drought and climate change-induced stressors was accomplished by Mech + Fire with the other treatments not completely meeting this goal but they still moved closer than untreated controls (Table 1, Figure 6). The costs of implementing these multiple pathways could be met by different landowners with co-objectives, such as producing revenue to pay for forest treatments, whereas other landowners could receive a subsidy to pay for the needed treatments (Table 2) or more funds could be invested in increasing forest resilience.

One key component to long-term forest conservation will be continued treatments to maintain or improve the conditions from forest restoration. The treatments done in this study represent approaches that reflect a strong commitment to stewardship from the landowner. Initial treatments are valuable only to the extent that they can lead to second, third, and an indefinite number of follow-up treatments. Many Indigenous people speak of "active stewardship" as one of the key principles in land management (Goode et al., 2022; Lightfoot et al., 2021) and this aligns well with the need for increased restoration in western US forests. If we do not use the knowledge from 20+ years of forest research and the much longer tradition of Indigenous cultural practices and knowledge, frequent-fire forests will continue to be degraded and lost. It is time to do the critical work needed to conserve our forests for the long term.

ACKNOWLEDGMENTS

We thank Bob Heald who was the manager at Blodgett Forest at the beginning of this study for his strong support. Without his talent and hard work this study would never have been accomplished. We also thank Frieder Schurr, Dave Rambo, Cheryl Rambo, Russell Seufert, Amy Mason, and Danny Fry for their assistance. This project could never have been done without the hard work of all of the graduate students, postdocs, Berkeley Forest staff, and forest technicians who worked on it over the years, we thank all of them. The US Joint Fire Sciences Program originally funded this project and also this Special Feature. Previous support from the California Fourth Climate Change Assessment, the McIntire-Stennis Program, the California Greenhouse Gas Reduction Fund, the UC Office of the President's UC Laboratory Fees Research Program, and Smart Practices and Architecture for Prescribed Fires in California was also important to keeping this long-term project active over the last 20-years.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data (Stephens, Foster, et al., 2023a) are available in Dryad at https://doi.org/10.5061/dryad.bzkh189gb. Code (Stephens, Foster, et al., 2023b) is available in Zenodo at https://doi.org/10.5281/zenodo.8429078.

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* 113: 11770–75.

Agee, J. K., and C. N. Skinner. 2005. "Basic Principles of Forest Fuel Reduction Treatments." *Forest Ecology and Management* 211: 83–96.

Allen, C. D., D. D. Breshears, and N. G. McDowell. 2015. "On Underestimation of Global Vulnerability to Tree Mortality and Forest Die-off from Hotter Drought in the Anthropocene." *Ecosphere* 6: 129.

Brown, J. K. 1974. *Handbook for Inventorying Downed Woody Material*. General Technical Report, INT-16. Ogden: USDA Forest Service, Forest and Range Experiment Station.

Bryant, T., K. Waring, A. Sanchez Meador, and J. B. Bradford. 2019. "A Framework for Quantifying Resilience to Forest Disturbance." *Frontiers in Forests and Global Change* 2: 56.

Busse, M. D., S. A. Simon, and G. M. Riegel. 2000. "Tree-Growth and Understory Responses to Low-Severity Prescribed Burning in Thinned *Pinus ponderosa* Forests of Central Oregon." *Forest Science* 46: 258–268.

Collins, B. M., H. A. Kramer, K. Menning, C. Dillingham, D. Saah, P. A. Stine, and S. L. Stephens. 2013. Modeling Hazardous Fire Potential within a Completed Fuel Treatment in the Northern Sierra Nevada. *Forest Ecology and Management* 310: 156–166.

Collins, B. M., D. L. Fry, J. M. Lydersen, R. Everett, and S. L. Stephens. 2017. "Impacts of Different Land Management Histories on Forest Change." *Ecological Applications* 27: 2475–86.

Cova, G., V. R. Kane, S. Prichard, M. North, and C. A. Cansler. 2023. "The Outsized Role of California's Largest Wildfires in Changing Forest Burn Patterns and Coarsening Ecosystem Scale." *Forest Ecology and Management* 528: 120620.

Covington, W. W., P. Z. Fule, M. M. Moore, S. C. Hart, T. E. Kolb, J. N. Mast, S. S. Sackkett, and M. R. Wagner. 1997. "Restoration of Ecosystem Health in Southwestern Ponderosa Pine Forests." *Journal of Forestry* 95: 23–29.

Foster, D. E. 2018. "Rfuels: Estimate Fuel Loads From Brown's Transects for Sierra Nevada Conifers." https://github.com/danfosterfire/Rfuels.

Foster, D. E., J. J. Battles, B. M. Collins, R. A. York, and S. L. Stephens. 2020. "Potential Wildfire and Carbon Stability in Frequent-Fire Forests in the Sierra Nevada: Trade-Offs from a Long-Term Study." *Ecosphere* 11(8): e03198.

Goode, R. W., S. F. Beard, and C. Oraftik. 2022. "Putting Fire on the Land: The Indigenous People Spoke the Language of Ecology, and Understood the Connectedness and Relationship between Land, Water, and Fire." *Journal of California and Great Basin Anthropology* 42(1): 85–95.

Graham, R. T., S. McCaffrey, and T. B. Jain, eds. 2004. *Science Basis for Changing Forest Structure to Modify Wildfire Behavior and Severity* 43. Fort Collins: USDA Forest Service Rocky Mountain Research Station General Technical Report, RMRS-120.

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(8): e02431.

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(1): 40.

Harmon, M. E., and R. J. Pabst. 2015. Testing Predictions of Forest Succession using Long-term Measurements: 100 years of Observations in the Oregon Cascades. *Journal of Vegetation Science* 26(4): 722–732.

Hartig, F. 2021. "DHARMa: Residual Diagnostics for Hierarchical (Multi-Level/Mixed) Regression Models." R Package Version 0.4.4. https://CRAN.R-project.org/package=DHARMa.

Hartsough, B. R., S. Abrams, R. J. Barbour, E. S. Drews, J. D. McIver, J. J. Moghaddas, D. W. Schwilk, and S. L. Stephens. 2008. "The Economics of Alternative Fuel Reduction Treatments in Western United States Dry Forests: Financial and Policy Implications from the National Fire and Fire Surrogate Study." *Forest Economics and Policy* 10: 344–354.

Hessburg, P. F., S. J. Prichard, R. K. Hagmann, N. A. Povak, and F. K. Lake. 2021. "Wildfire and Climate Change Adaptation of Western North American Forests: A Case for Intentional Management." *Ecological Applications* 31: 02432.

Jones, G. M., R. J. 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.

Kalies, E. L., and L. L. Y. Kent. 2016. "Tamm Review: Are Fuel Treatments Effective at Achieving Ecological and Social Objectives? A Systematic Review." *Forest Ecology and Management* 375: 84–95.

Keane, R. E., R. A. Loehman, L. M. Holsinger, D. A. Falk, P. Higuera, S. M. Hood, and P. F. Hessburg. 2018. "Use of Landscape Simulation Modeling to Quantify Resilience for Ecological Applications." *Ecosphere* 9(9): e02414.

Knapp, E. E., A. A. Bernal, J. M. Kane, C. J. Fettig, and M. P. North. 2021. "Variable Thinning and Prescribed Fire Influence Tree Mortality and Growth during and after a Severe Drought." *Forest Ecology and Management* 479: 118595.

Lightfoot, K. G., R. Cuthrell, M. G. Hylkema, V. Lopez, D. Gifford-Gonzalez, R. A. Jewett, M. A. Grone, et al. 2021. "The Eco-Archaeological Investigation of Indigenous Stewardship Practices on the Santa Cruz Coast." *Journal of California and Great Basin Anthropology* 41(2): 187–205.

Long, J. N. 1985. "A Practical Approach to Density Management." *The Forestry Chronicle* 61: 23–27.

Long, J. N., and J. D. Shaw. 2005. "A Density Management Diagram for Even-Aged Ponderosa Pine Stands." *Western Journal of Applied Forestry* 20: 1–11.

Long, J. N., and J. D. Shaw. 2012. "A Density Management Diagram for Even-Aged Sierra Nevada Mixed-Conifer Stands." *Western Journal of Applied Forestry* 27: 187–195.

McGinnis, T. W., C. D. Shook, and J. E. Keeley. 2010. "Estimating Aboveground Biomass for Broadleaf Woody Plants and Young Conifers in Sierra Nevada, California, Forests." *Western Journal of Applied Forestry* 25: 203–9.

McIver, J., S. Stephens, J. Agee, J. Barbour, R. Boerner, C. Edminster, K. Erickson, et al. 2012. "Ecological Effects of Alternative Fuel Reduction Treatments: Highlights of the U.S. Fire and Fire Surrogate Study." *International Journal of Wildland Fire* 22: 63–82.

Minnich, R. A., M. G. Barbour, J. H. Burk, and R. F. Fernau. 1995. "Sixty Years of Change in Californian Conifer Forests of the San Bernardino Mountains." *Conservation Biology* 9: 902–914.

Moghaddas, E., and S. L. Stephens. 2007. "Thinning, Burning, and Thin-Burn Fuel Treatment Effects on Soil Properties in a Sierra Nevada Mixed-Conifer Forest." *Forest Ecology and Management* 250: 156–166.

Moghaddas, J. J., R. A. York, and S. L. Stephens. 2008. "Initial Response of Conifer and California Black Oak Seedlings Following Fuel Reduction Activities in a Sierra Nevada Mixed Conifer Forest." *Forest Ecology and Management* 255: 3141–50.

Muukkonen, P., R. Mäkipää, R. Laiho, K. Minkkinen, H. Vasander, and L. Finér. 2006. "Relationship between Biomass and Percentage Cover in Understory Vegetation of Boreal Coniferous Forests." *Silva Fennica* 40: 231–245.

North, M., J. Innes, and H. Zald. 2007. "Comparison of Thinning and Prescribed Fire Restoration Treatments to Sierran Mixed-Conifer Historic Conditions." *Canadian Journal of Forest Research* 37: 331–342.

North, M., R. E. Tompkins, A. A. Bernal, B. M. Collins, S. L. Stephens, and R. A. York. 2021. "Operational Resilience in Western US Frequent-Fire Forests." *Forest Ecology and Management* 507: 120004.

North, M. P., B. M. Collins, and S. L. Stephens. 2012. "Using Fire to Increase the Scale, Benefits and Future Maintenance of Fuels Treatments." *Journal of Forestry* 110: 392–401.

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(22): 2020GL089858.

Parks, S. A., L. M. Holsinger, M. H. Panunto, W. M. Jolly, S. Z. Dobrowski, and G. K. Dillon. 2018. "High-Severity Fire: Evaluating its Key Drivers and Mapping its Probability across Western US Forests." *Environmental Research Letters* 13(4): 044037.

Peterson, D. L., S. S. Sackett, L. J. Robinson, and S. M. Haase. 1994. "The Effects of Repeated Prescribed Burning on Ponderosa Pine Growth." *International Journal of Wildland Fire* 4: 239–247.

Reineke, L. H. 1933. "Perfecting a Stand-Density Index for Even-Aged Forests." *Journal of Agriculture Research* 46: 627–638.

Reinhardt, E. D., and N. L. Crookston. 2003. "The Fire and Fuels Extension to the Forest Vegetation Simulator." United States Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Rebain, S. A. 2015. The Fire and Fuels Extension to the Forest Vegetation Simulator: Updated Model Documentation. USDA Forest Service, Forest Management Service Center, For Collins, CO. 403.

Safford, H. D., A. K. Paulson, Z. L. Steel, D. J. N. Young, and R. B. Wayman. 2022. "The 2020 California Fire Season: A Year like no Other, a Return to the Past or a Harbinger of the Future?" *Global Ecology and Biogeography* 31: 2005–25.

Safford, H. D., and J. T. Stevens. 2017. *Natural Range of Variation for Yellow Pine and Mixed-Conifer Forests in the Sierra Nevada, Southern Cascades, and Modoc and Inyo National Forests, California, USA*. General Technical Reports PSW-GTR-256, Vol. 229, 256. Albany: US Department of Agriculture, Forest Service, Pacific Southwest Research Station.

Scherer, S. S., A. W. D'Amato, C. C. Kern, B. J. Palik, and M. B. Russell. 2016. "Long-Term Impacts of Prescribed Fire on Stand Structure, Growth, Mortality, and Individual Tree Vigor in *Pinus resinosa* Forests." *Forest Ecology and Management* 368: 7–16.

Schielzeth, H., N. J. Dingemanse, S. Nakagawa, D. F. Westneat, H. Allegue, C. Teplitsky, D. Réale, N. A. Dochtermann, L. Z. Garamszegi, and Y. G. Araya-Ajoy. 2020. "Robustness of Linear Mixed-Effects Models to Violations of Distributional Assumptions." *Methods in Ecology and Evolution* 11: 1141–52.

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." USDA Forest Service—General Technical Report RMRS-GTR:1–76.

Spies, T. A., M. A. Hemstrom, A. Youngblood, and S. Hummel. 2006. "Conserving Old-Growth Forest Diversity in Disturbance-Prone Landscapes." *Conservation Biology* 20: 351–362.

Stark, D. T., D. L. Wood, A. J. Storer, and S. L. Stephens. 2013. "Prescribed Fire and Mechanical Thinning Effects on Bark Beetle Caused Tree Mortality in a Mid-Elevation Sierran Mixed-Conifer Forest." *Forest Ecology and Management* 306: 61–67.

Steel, Z. L., M. J. Goodwin, M. D. Meyer, G. A. Fricker, H. S. J. Zald, M. D. Hurteau, and M. P. North. 2021. "Do Forest Fuel Reduction Treatments Confer Resistance to Beetle Infestation and Drought Mortality?" *Ecosphere* 12: e03344.

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.

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(1): 1–23.

Stephens, S., D. Foster, J. Battles, A. Bernal, B. Collins, R. Hedges, J. Moghaddas, A. Roughton, and R. York. 2023a. "Forest Restoration and Fuels Reduction Work: Different Pathways for Achieving Success in the Sierra Nevada." Dryad, Dataset. https://doi.org/10.5061/dryad.bzkh189gb.

Stephens, S., D. Foster, J. Battles, A. Bernal, B. Collins, R. Hedges, J. Moghaddas, A. Roughton, and R. York. 2023b. "Forest Restoration and Fuels Reduction Work: Different Pathways for Achieving Success in the Sierra Nevada." Zenodo, Software. https://doi.org/10.5281/zenodo.8429078.

Stephens, S. L., M. A. Battaglia, D. J. Churchill, B. M. Collins, M. Coppoletta, C. M. Hoffman, J. M. Lydersen, et al. 2021. "Forest Restoration and Fuels Reduction: Convergent or Divergent?" *Bioscience* 71: 85–101.

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.

Stephens, S. L., and B. M. Collins. 2004. "Fire Regimes of Mixed Conifer Forests in the North-Central Sierra Nevada at Multiple Spatial Scales." *Northwest Science* 78: 12–23.

Stephens, S. L., L. Hall, C. W. Stephens, A. A. Bernal, and B. M. Collins. 2023. "Degradation and Restoration of Indigenous

California Black Oak (*Quercus kelloggii*) Stands in the Northern Sierra Nevada." *Fire Ecology* 19: 12. https://doi.org/10.1186/s42408-023-00172-9.

Stephens, S. L., J. M. Lydersen, B. M. Collins, D. L. Fry, and M. D. Meyer. 2015. "Historical and Current Landscape-Scale Ponderosa Pine and Mixed-Conifer Forest Structure in the Southern Sierra Nevada." *Ecosphere* 6(5): art 79.

Stephens, S. L., J. D. McIver, R. E. J. Boerner, C. J. Fettig, J. B. Fontaine, B. R. Hartsough, P. Kennedy, and D. W. Schwilk. 2012. "Effects of Forest Fuel Reduction Treatments in the United States." *BioScience* 62: 549–560.

Stephens, S. L., J. D. Miller, B. M. Collins, M. P. North, J. J. Keane, and S. L. Roberts. 2016. "Wildfire Impacts on California Spotted Owl Nesting Habitat in the Sierra Nevada." *Ecosphere* 7(11): e01478.

Stephens, S. L., and J. J. Moghaddas. 2005. "Experimental Fuel Treatment Impacts on Forest Structure, Potential Fire Behavior, and Predicted Tree Mortality in a Mixed Conifer Forest." *Forest Ecology and Management* 215: 21–36.

Stephens, S. L., J. J. Moghaddas, C. Ediminster, C. E. Fiedler, S. Hasse, 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.

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(8): 081004.

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.

Wang, J. A., J. T. Randerson, M. L. Goulden, C. A. Knight, and J. J. Battles. 2022. "Losses of Tree Cover in California Driven by Increasing Fire Disturbance and Climate Stress." *AGU Advances* 3(4): e2021AV000654.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. "Warming and Earlier Spring Increase Western US Forest Wildfire Activity." *Science* 313: 940–43.

York, R. A., J. Levine, D. Foster, S. Stephens, and B. Collins. 2021. "Silviculture Can Facilitate Repeat Prescribed Burn Programs with Long-Term Strategies." *California Agriculture* 75(4): 104–111.

York, R. A., K. W. Russell, and H. Noble. 2022. "Merging Prescribed Fires and Timber Harvests in the Sierra Nevada: Burn Season and Pruning Influences in Young Mixed Conifer Stands." *Trees, Forests, and People* 9: 100309. https://doi.org/10.1016/j.tfp.2022.100309.

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: Stephens, Scott L., Daniel E. Foster, John J. Battles, Alexis A. Bernal, Brandon M. Collins, Rachelle Hedges, Jason J. Moghaddas, Ariel T. Roughton, and Robert A. York. 2023. "Forest Restoration and Fuels Reduction Work: Different Pathways for Achieving Success in the Sierra Nevada." *Ecological Applications* e2932. https://doi.org/10.1002/eap.2932