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# Shaded fuel breaks create wildfire-resilient forest stands: lessons from a long-term study in the Sierra Nevada

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## Abstract

**Background** In California's mixed-conifer forests, fuel reduction treatments can successfully reduce fire severity, bolster forest resilience, and make lasting changes in forest structure. However, current understanding of the duration of treatment effectiveness is lacking robust empirical evidence. We leveraged data collected from 20-year-old forest monitoring plots within fuel treatments that captured a range of wildfire occurrence (i.e., not burned, burned once, or burned twice) following initial plot establishment and overstory thinning and prescribed fire treatments.

**Results** Initial treatments reduced live basal area and retained larger-diameter trees; these effects persisted throughout the 20-year study period. Wildfires maintained low surface and ground fuel loads established by treatments. Treatments also reduced the probability of torching immediately post-treatment and 20 years post initial thinning treatments.

**Conclusions** Fuel treatments in conifer-dominated forests can conserve forest structure in the face of wildfire. Additionally, findings support that the effective lifespans of treatments can be extended by wildfire occurrence. Our results suggest that continued application of shaded fuel breaks is not only a sound strategy to ensure forest persistence through wildfire but may also be compatible with restoration objectives aimed at allowing for the use of more ecologically beneficial fire across landscapes.

**Keywords** Fuel management, Forest restoration, Treatment efficacy, Forest structure, Wildfire

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**Resumen**

**Antecedentes** En los bosques mixtos de coníferas de California, los tratamientos de reducción de combustibles pueden atenuar exitosamente la severidad del fuego, robustecer la resiliencia, y hacer más durables los cambios en la estructura forestal.

Desde luego, el entendimiento actual sobre la duración de la efectividad de estos tratamientos carece de una evidencia empírica robusta.

Aprovechamos datos coleccionados en parcelas de monitoreo dentro de tratamientos de reducción combustible en bosques de veinte años de antigüedad que capturaban un rango de ocurrencia de incendios (i.e. no quemados, quemados una vez, o dos veces) luego del establecimiento de las parcelas y también tratamientos de poda del dosel y quemas prescriptas.

**Resultados** Los tratamientos iniciales redujeron el área basal viva y retuvieron árboles con diámetros grandes: estos efectos perduraron a través de los veinte años de estudio. Los incendios mantuvieron una carga baja en los combustibles superficiales establecidas por los tratamientos.

Los tratamientos también redujeron la probabilidad de ocurrencia de fuegos de copa inmediatamente después de su aplicación y también luego de veinte años de haber sido efectuados los tratamientos de poda del dosel.

**Conclusiones** Los tratamientos de combustibles en bosques dominados por coníferas pueden conservar la estructura forestal en respuesta a incendios. Adicionalmente, los resultados confirman que la vida media de los tratamientos puede ser extendida mediante la ocurrencia de incendios forestales. Nuestros resultados también sugieren que la aplicación continua de barreras de combustible sombreadas no es sólo una estrategia sensata para asegurar la persistencia del bosque entre incendios, sino que también puede ser compatible con objetivos de restauración para un uso más beneficioso del fuego ecológico a través de diferentes paisajes.


## Background

Contemporary conditions in western US frequent-fire forests (fire return intervals < 35 years; North et al. 2022) have increased the likelihood and size of high severity effects in wildfires, which can alter forest structure and successional dynamics (Keane et al. 2008; Miller et al. 2009; Parks and Abatzoglou 2020; Hagmann et al. 2021). Fuel reduction treatments can reduce wildfire impacts on forests (Agee and Skinner 2005), bolster suppression efforts (Agee et al. 2000), and improve firefighter safety (Moghaddas and Craggs 2007). In high fire hazard forests, the application of thinning treatments followed by prescribed fire can create fire resistant forest structures by reducing stand densities (Stephens et al. 2009), retaining larger-diameter, fire-resistant trees with greater crown base heights (Agee and Skinner 2005), and decreasing surface and ladder fuels (Schwilk et al. 2009; Hood 2010). Mainly, these changes enhance managers' ability to accommodate the effects of wildfire on the landscape and promote overall forest resilience by allowing ecosystems to maintain their basic structure and function amid disturbance and eventually return to similar structure and composition post-disturbance (Stephens et al. 2012; DeRose and Long 2014; Tubbesing et al. 2019; Steel et al. 2021).

Fuel treatments in dry, conifer forests in the Sierra Nevada have a lifespan of approximately 10–20 years, after which the ingrowth of understory trees and accumulation of downed woody fuels can diminish their efficacy (Stephens et al. 2012; Martinson and Omi 2013; Foster et al. 2020). Within a treatment's effective lifespan, hazardous potential fire behavior and effects can be reduced within treated units and their surrounding areas (Collins et al. 2011; Tubbesing et al. 2019). Ultimately, treatment efficacy depends on both the scale at which treatments are applied on the landscape and the ability for units to be maintained over time. Ideally, initial treatments would create forest conditions that would allow for wildfire to resume a more natural role in these ecosystems (Reinhardt et al. 2008; North et al. 2012, 2015; Stevens et al. 2014). However, real-world limitations to forest restoration (e.g., operational constraints, managing for other resource protection measures) often limit the extent and intensity of planned treatments, thus limiting their ability to meet stated objectives (sensu Stephens et al. 2016; Vaillant and Reinhardt 2017; Lydersen et al. 2019). Gaining empirical information about the longer-term influences of wildfire on fuel treatment structure and effectiveness can provide land managers information regarding long-term efficacy of treatments and tradeoffs between managing for a multitude of objectives.

This study aimed to understand forest structural change over a 20-year period in areas treated for fuel reduction and assess how wildfire occurrence in these treated areas impacted change over time. We leveraged data collected from long-term forest monitoring plots within fuel treatments that captured a range of wildfire occurrence (i.e., not burned, burned once, or burned twice) following the application of initial thinning treatments and prescribed fire. By assessing the impacts of both treatments and wildfires on forest structure in the short- and long-term, this project evaluated real-world implementations of treatments subject to stringent resource constraints to meet stated objectives. We expected treatments and wildfire occurrence to reduce forest stocking rates and surface fuel loads. We also hypothesized wildfire occurrence would reduce the future likelihood of torching within each unit, therefore extending the effective lifespan of the treatment. We also expected that in the absence of subsequent wildfire, the impact of treatments on forest structure and future likelihood of torching fire may diminish over time. To test our hypotheses, we used a combination of data from permanently monumented field plots measured across three time periods: pre-treatment, 1-year post-treatment, and approximately 20-years post-initial-thinning-treatments. The primary goals of this study were to (1) evaluate how shaded fuel breaks impact forest stand structure both post-treatment and post-wildfire and (2) determine if wildfire occurrence extends the effective lifespan of a shaded fuel break.

## Methods

### Study sites

The study sites are in the northeastern portion of the Plumas National Forest, which is situated in the northern Sierra Nevada, California, USA (Fig. 1; Table S1). Elevation ranges from 1524 to 1936 m with slope gradients varying from 3 to 23%. The vegetation is characterized as fire-excluded upper elevation eastside pine, which prior to treatments was dominated by yellow pine (*Pinus ponderosa*, 35%, *P. jeffreyi*, 28%), white fir (*Abies concolor*, 35%),, lodgepole pine (*P. contorta* ssp. *Murrayana*, 1%), and incense-cedar (*Calocedrus decurrens*, 1%). These percentages were derived from basal area proportions based on pre-treatment plot data (described in the following). The regional climate is characterized as Mediterranean with cool, wet winters and hot, dry summers. At Antelope Lake, CA (Fig. 1), the mean annual temperature is 8.2 °C, and mean annual precipitation is 614 mm with most of it falling as snow from December to March with little rain between May and October (PRISM Climate Group 2022). Study sites were selected from long-term forest monitoring plots located within a network of shaded fuel breaks (Weatherspoon and Skinner 1996) established by the Herger-Feinstein Quincy Library Group Forest Recovery Act and Pilot Project (HFQLG; 1998; Consolidated Appropriations Act, 2008 (H.R. 2764)). Prior to 1850, these eastern pine-dominated forests experienced frequent, low-moderate severity fires every 8–22 years (Moody et al. 2006) but have since been significantly altered by fire exclusion (Lydersen and Collins 2018). Treatments were implemented to reduce wildfire risk and improve forest health, which involved removing understory trees, retaining larger trees, and treating activity and natural fuels (USDA-FS 2001).

Additionally, sites were selected based on exposure to wildfires following treatment application, resulting in a mix of low- and moderate-severity effects (further explanation is provided in the following and in Table S2). Three treatment units in the Antelope Border (AB) shaded fuel break were burned by the 2006 Boulder Complex Fire, which started on June 25, 2006, and burned 1513 ha. Two other units within the AB shaded fuel break were burned by the Antelope Complex Fire, that started on July 5, 2007, and burned 9486 ha and was reburned by the 2019 Walker Fire, which was 23,992 ha and started on September 4, 2019. Treatment units within the Red Clover (RC) shaded fuel break were not exposed to wildfire following initial treatment application and were also used in this study.

### Treatments

From 2001 to 2002, shaded fuel breaks were implemented following the goals outlined in the Record of Decision for the HFQLG Act. Shaded fuel breaks are a type of fuel treatment prescription between 0.4 and 0.8 km in width, treated with a combination of mechanical thinning from below and prescribed fire, and commonly located adjacent to existing features such as roads and ridgetops (Agee et al. 2000; Kennedy et al. 2019). Treatments aimed to reduce the probability of crown fires by removing trees ≤ 50.8 cm, particularly focusing on the removal of 90% of smaller trees that could act as ladder fuels. Surface fuels (i.e., smaller diameter materials ≤ 27.9 cm) would be reduced to ≤ 22.4 $Mgha^{-1}$ Often the implementation of planned treatments face real-world constraints that force logistical accommodations (e.g., Lydersen et al. 2019; Low et al. 2021); the Antelope Border and Red Clover shaded fuel breaks were no exception. Thus, a gradient of treatment intensities was implemented across units (Table 1).

### Vegetation and fuels measurements

In 2001, a network of monitoring plots was established in treatment units that had existing approved treatment plans. Vegetation and fuels data for these plots were collected in 2001 (pre-treatment), from 2003 to 2009 (1-year post-treatment), and in 2021 (approximately 20-years post-initial-treatment; Fig. 2). Sampling

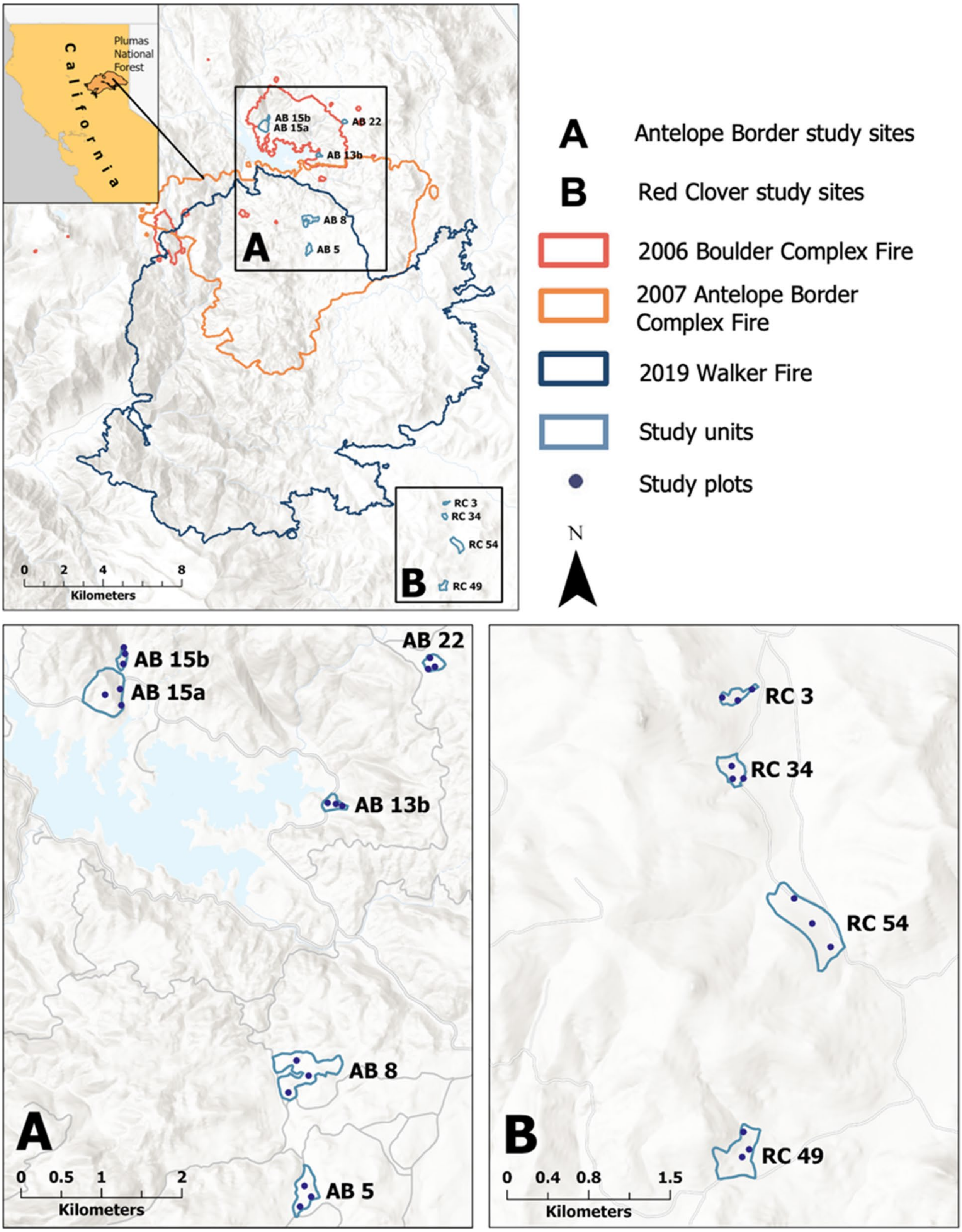


**Fig. 1** Map of study sites, which are located within the Antelope Border (AB) and Red Clover (RC) shaded fuel breaks in the northeastern portion of the Plumas National Forest, CA, USA. The upper left panel shows study units and footprints of the three wildfires in this study: the 2006 Boulder Complex Fire, 2007 Antelope Complex Fire, and 2019 Walker Fire. The lower left panel (**A**) shows study units within the Antelope Border shaded fuel break. The lower right panel (**B**) shows study units within the Red Clover shaded fuel break

**Table 1** Treatment and wildfire exposure descriptions for study units in the Plumas National Forest. Treatment type refers to initial thinning treatment method applied, which includes either a mechanical thin from below or hand thinning. Treatment intensity is a calculated metric and refers to the percent change in live basal area 1-year post-thinning relative to pre-treatment levels (Low et al. 2021). Positive values indicate reductions, while negative values indicate increases in basal area. Wildfires include the 2006 Boulder Complex Fire, 2007 Antelope Complex Fire, and 2019 Walker Fire

| Unit | Treatment type | Year of treatment | Treatment intensity (% live BA changed) | Activity fuel treatment | Year of activity fuel treatment | Wildfire count |
|---|---|---|---|---|---|---|
| AB5 | Mechanical | 2001 | 49.5 | Underburn | 2002 | Antelope and Walker |
| AB8 | Mechanical | 2001 | 63.7 | Underburn | 2002 | Antelope and Walker |
| AB13b | Mechanical | 2001 | 8.1 | Underburn | 2001 | Boulder |
| AB15a | Mechanical | 2001 | −3.8 | Underburn | 2001 | Boulder |
| AB15b | Mechanical | 2001 | 28.2 | Underburn | 2001 | Boulder |
| AB22 | Mechanical | 2002 | 44.3 | Underburn | 2002 | NA |
| RC3 | Hand thin | 2001 | −5.5 | Underburn | 2009 | NA |
| RC34 | Hand thin | 2001 | 25.2 | Underburn | 2008 | NA |
| RC49 | Hand thin | 2001 | −0.8 | Underburn | 2008 | NA |
| RC54 | Hand thin | 2001 | 43.9 | Underburn | 2008 | NA |

plots ($n=29$) consisted of a nested sampling design. Live trees ≥ 76.2 cm diameter at breast height (DBH; breast height = 1.37 m) were recorded within a 0.1 ha rectangular plot. Live trees 40.6–76.1 cm DBH and 12.7–40.5 cm DBH were recorded within embedded plots of 0.05 ha and 0.025 ha, respectively. Snags, defined as standing dead trees > 3 m tall, were also measured using the same nested plot. Live trees 2.54–12.6 cm DBH were recorded within 5 embedded plots each 0.001 ha. Downed woody surface fuels and duff were sampled using two methods. Within the total area of each 0.025 ha plot, estimates of weight (Mgha$^{-1}$) for three size classes (0–2.54 cm, 2.55–7.62 cm, and 7.63–22.86 cm) were recorded using the photo series method (Blonski and Schramel 1981). In 2021, we used the line intercept method (Brown 1974), collecting individual counts of 1-h (0–0.64 cm) and 10-h (0.64–2.54 cm) fuels from 3 to 5 m and 100-h (2.54–7.62 cm) fuels from 3 to 7 m; we recognize that sampling 100-h fuels from 3 to 7 m may under sample the variability of this fuel class (Sikkink and Keane 2008). We sampled 1000-h fuels along the entirety of the 15 m transect. Diameter and decay class were recorded for coarse woody debris (1000-h), while duff and litter depth (cm) were measured 5 and 7 m from plot center.

We calculated live basal area (m$^2$ha$^{-1}$) and live quadratic mean diameter (QMD; cm) to evaluate how differences in wildfire exposure influenced forest structure within treatment units. To evaluate the current state of fuelbed characteristics in 2021, we calculated fuel load (Mgha$^{-1}$) estimates of fine woody debris (1–100-h fuels and litter), coarse woody fuel (≥ 1000-h fuels; CWD), and duff from each plot ($n=29$) by inputting line intercept method data into species-weighted formulas derived in *Rfuels* (Van Wagtendonk et al. 1996, 1998; Stephens 2001; Foster 2018).

### Probability of torching

We used the Western Sierra variant of the Forest Vegetation Simulator (FVS; Wykoff et al. 1982) with the Fire and Fuels Extension (FFE; Reinhardt and Crookston 2003) to calculate the probability of torching (P-Torch) for each plot at each measurement year. P-Torch is the probability of a small area torching in a forest stand. Following the methods of fuel model selection outlined in Collins et al. (2011, 2013), we used plot-derived forest stand structure characteristics, which included using photo series-derived fuelbed estimates, to select fuel models for each measurement year. Break points for both pre-treatment and 20-years post-treatment basal area, (m$^2$ha$^{-1}$), tree density (trees ha$^{-1}$), shrub cover (%), and woody surface fuel loads (Mgha$^{-1}$) were identified using a combination of structural conditions for untreated stands listed in (Collins et al. 2013) and our observed values. Breaks were used to bin plots into discrete Scott and Burgan (2005) fuel models (Fig. S1). For the 1-year post-treatment measurement period, we used fuel model assignments for similar HFQLG shaded fuel break units listed in Collins et al. (2013) where stands that were either mechanically thinned and prescription burned (timber-litter fuel model) or hand thinning and pile burned (light slash fuel model) were assigned. All plots were assigned a high and low fuel model to account for the uncertainty associated


**Fig. 2** Photo comparison of treatment units in the Antelope Border shaded fuel break by measurement year and wildfire count. All units shown were mechanically thinned followed by prescribed fire. The 5-year post-treatment photos capture stand conditions less than 1-year post-wildfire (2006 Boulder Complex Fire for 1 Wildfire unit and 2007 Antelope Complex Fire for 2 Wildfires unit). The 20-year post-treatment photos capture 15-year post-fire for the 1 Wildfire unit and 2-year post-fire (2019 Walker Fire) for 2 Wildfires unit

with surface fuel model assignment and the influence of selected models on predicted fire behavior (Chiono et al. 2017). High fuel models predict more intense fire behavior (e.g., greater flame lengths and scorch heights) while low models produced milder behavior. We then verified assigned models using local expert knowledge. Modeled fire behavior outputs for each plot per measurement period were the average of high and low surface fuel model runs.

### Design and analysis

We appreciated the challenge of extracting robust information from a quasi-experiment where the "treatment" is the occurrence of a wildfire. Moreover, we recognized that the initial pre- and post-treatment measurements were primarily designed to quantify the implementation of the shaded fuel breaks, not their long-term effectiveness. Thus, our repurposing of the initial design was done with appropriate caution (sensu Block et al. 2001). These cautions include the following: (1) lumping wildfire exposure into broad categorical variables, (2) employing robust statistical analyses, (3) providing multiple metrics that evaluate the fit of our models and the weight of evidence for observed fixed effects.

We applied an information-theoretic approach (Burnham and Anderson 2002) to assess the impacts of wildfire exposure and time since initial thinning treatments on forest structure characteristics and probability of torching. We evaluated four time- and wildfire-related explanatory (i.e., fixed) variables in our analyses. We accounted for site-level differences by including a random intercept term in all our models. Given our limited sample size, 29 plots distributed over 10 sites, we only considered model

**Table 2** Overview of statistical analyses implemented for each response variable, explanatory variables included in the final model (model with lowest AICc score), conditional and marginal $R^2$ values, and AIC weight for each final model

| Response variable | Model type | Transformation applied | Variables in final model | Conditional $R^2$ | Marginal $R^2$ | AIC weight |
|---|---|---|---|---|---|---|
| **Residual live basal area** ($m^2ha^{-1}$) | Linear mixed-effects | Square root | Measurement timing, wildfire occurrence, interaction term | 0.26 | 0.25 | 0.45 |
| **Live QMD** (cm) | Linear mixed-effects | NA | Measurement timing, wildfire occurrence, interaction term | 0.43 | 0.39 | 0.85 |
| **Fine fuels** (1-, 10-, 100-h fuels, and litter; $Mgha^{-1}$) | Linear mixed-effects | NA | Averaged severity | 0.38 | 0.38 | 0.52 |
| **CWD** (≥ 1000-h fuels; $Mgha^{-1}$) | Linear mixed-effects | Square root | Wildfire occurrence | 0.14 | 0.14 | 0.44 |
| **Duff** ($Mgha^{-1}$) | Linear mixed-effects | Square root | Averaged severity | 0.43 | 0.34 | 0.52 |
| **P-Torch** | Generalized linear mixed-effects | Binomial distribution with log-link function | Measurement timing | 0.97 | 0.97 | 0.50 |

combinations with a maximum of three main effect terms with only two-way interaction terms. All models were compared using Akaike information criterion for smaller sample sizes (AICc). We used AICc to avoid fitting models that were overly complex given the size of the dataset (Burnham and Anderson 2002). All models within 2 AICc scores of the best model (i.e., ΔAICc) were considered to have substantial evidentiary support.

We also calculated the AIC weights for each model. We used these model weights to estimate the relative importance of variables under consideration. Specifically, we summed AIC weights for each model in which that variable appears as the measure of relative importance (Symonds and Moussalli 2011). Finally, we calculated the conditional and marginal goodness of fit ($R^2$) to provide insight on how much of the observed variance our best model explains. Conditional and marginal $R^2$ were estimated using the *MuMIn* package in *R* (Nakagawa et al. 2017; Bartoń 2022).

We used linear mixed-effects models in R (*lme4*; Bates et al. 2015; R Core Team 2018) to analyze overstory structure and fuels. For P-Torch results, we used generalized linear mixed-effects models. Initial analysis of response variables (Kassambara 2020) suggested that live QMD met the assumptions of linear models; however, we square-root-transformed live basal area data to meet model assumptions.

We defined the null model as one that included only treatment unit as a random effect. Using live basal area and live QMD as our response variables, we constructed additional models using four explanatory variables: measurement timing, wildfire occurrence, treatment intensity, and average wildfire severity. Measurement timing refers to the measurement period relative to the completion of initial thinning treatments, wildfire occurrence describes the number of times a plot has burned in a wildfire since initial thinning application in 2001 (i.e., not burned, burned once, or burned twice), and treatment intensity is the percent change in live basal area 1-year post-thinning treatment relative to pre-treatment levels. Average wildfire severity was calculated by averaging all pixel values of the relative differenced normalized burn ratio (RdNBR) that intersected the plot boundary, then assigning a fire severity class (i.e., low, moderate, high) using the composite burn index thresholds (Miller and Thode 2007; Lydersen et al. 2016). For plots burned by multiple wildfires, all RdNBR values from each fire were averaged. Within models, the four explanatory variables were analyzed as independent fixed terms, in combination with each other and with two-way interaction terms.

Because we to evaluated impacts of wildfire on downed woody surface and duff only at the 2021 measurement year, fuel analyses did not include the measurement timing variable. Although fine fuel (1-, 10-, 100-h fuels and litter) data met linear model assumptions, we log- and square-root-transformed CWD and duff data to meet model assumptions. Fuel analyses followed similar model structures as prior analyses. We also used generalized linear mixed-effects models with a binomial distribution and log-link function to evaluate the influence of time and wildfire exposure on P-Torch, which is a proportional variable. Models evaluating P-Torch included all four explanatory variables in the same combinations as prior analyses.

## Results

When selecting our top models, 4 of the 6 top models had a $\Delta AIC_c < 2$. Although there was not strong evidence for a single best model, we reported on the models with the lowest AICc scores below (Table 2) and have ranked

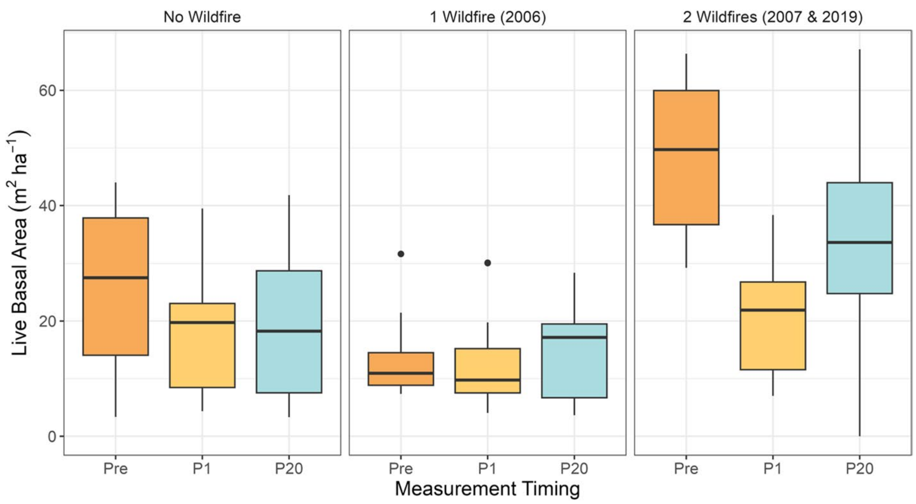


**Fig. 3** Average plot-level live basal area (m$^2$ha$^{-1}$) by measurement timing and wildfire exposure since treatments were implemented. Actual measurement years for these periods were as follows: 2001 for pre-treatment (Pre), 2003–2009 for 1-year post-treatment (P1), and 2021 for approximately 20-year post initial thinning treatments (P20). Plots have either not burned, burned once (2006), or twice (2007 and 2019) since plot establishment in 2001. The lower and upper limits of the box represent the first and third quartile of the data and the horizontal line is the median of the data. The vertical lines represent the 1.5 × interquartile range from the first and third quartile and the points represent data outside 1.5 × the interquartile range from the first and third quantiles

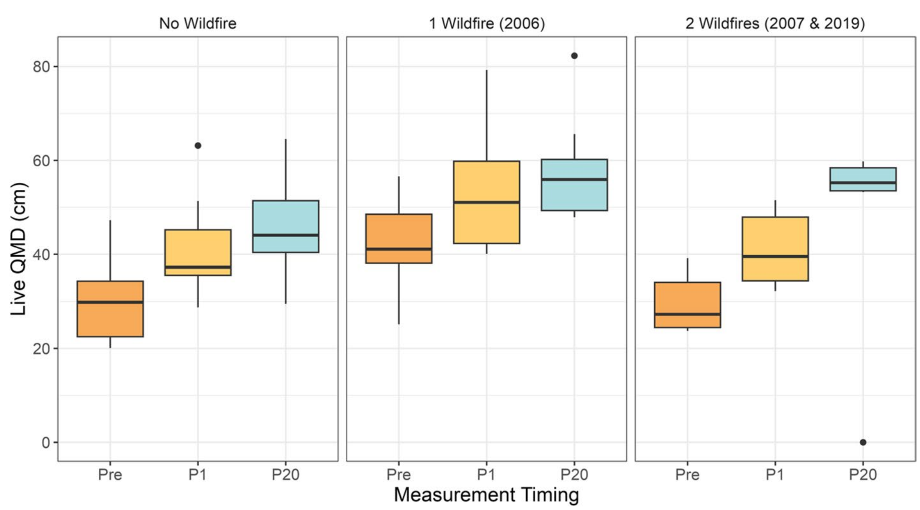


**Fig. 4** Average plot-level live QMD (cm) by measurement timing and wildfire exposure since treatments were implemented. Actual measurement years for these plots were: 2001 for pre-treatment (Pre), 2003–2009 for 1-year post-treatment (P1), and 2021 for approximately 20-years post initial thinning treatments (P20). Plots have either not burned, burned once (2006), or twice (2007 and 2019) since plot establishment in 2001

all models per response variable in the supplementary materials.

## Stand structure

### *Overstory stand structure*

Our top model for live basal area indicated that an interaction between measurement timing (relative importance [RI] = 0.87) and wildfire occurrence (RI = 0.75) influenced live basal area ($\Delta AIC_c = 1.4$; Table S4). Initial treatments decreased live basal area by an average of 34.6%, while live basal area increased by 24.3% in the period between the initial post-treatment and 2021 measurements. Despite five units experiencing one or two wildfires during the study period, 2021 averaged estimates of live basal area in unburned units were 19.9 m$^2$ha$^{-1}$, while estimates in units burned once and twice were 15.8 m$^2$ha$^{-1}$ and 33.9 m$^2$ha$^{-1}$ respectively (Fig. 3).

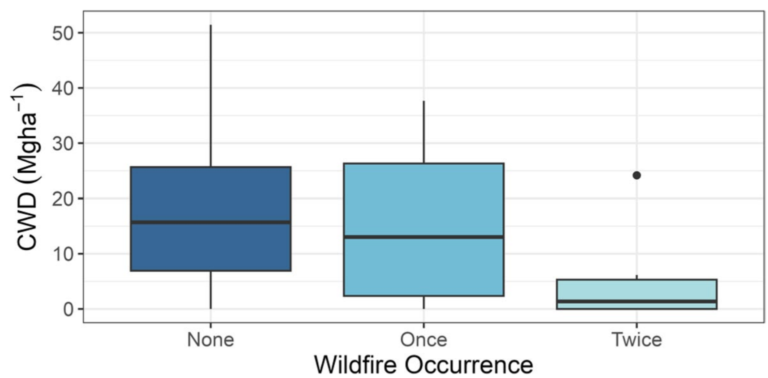


**Fig. 5** Averaged plot-level coarse woody debris (CWD) estimates (Mgha$^{-1}$) by wildfire occurrence. CWD includes 1000-h fuels. Plots have either not burned, burned once (2006), or twice (2007 and 2019) since plot establishment in 2001

The top model for live QMD indicated that an interaction between measurement timing (RI = 1.00) and wildfire occurrence (RI = 0.86) affected live QMD values ($\Delta AIC_c = 3.6$; Table S5). Initial thinning treatments increased live QMD by an average of 31.6% and live QMD continued to increase by 10.3% in the period between the initial post-treatment and 2021 measurements. In 2021, mean estimates of live QMD in unburned units was 45.3 cm, while estimates in units burned once and twice were 57.7 cm and 47.1 cm, respectively (Fig. 4).

### *Fuel loads in 2021*

The top model for CWD indicated that wildfire occurrence (RI = 0.47) affected coarse woody debris loads ($\Delta AIC_c = 0.3$; Table S6). In 2021, units that burned once and units that burned twice had 9.1% and 69.9% less CWD than unburned plots, respectively (Fig. 5). Models with the lowest AICc for fine fuels ($\Delta AIC_c = 0.3$; Table S7) and duff ($\Delta AIC_c = 0.4$; Table S8) included averaged wildfire severity. Averaged severity influenced fine fuels (RI = 0.54; Table S7) and duff (RI = 0.53; Table S8). In 2021, plots that burned at an average of low severity had 46.3% less fine fuels and 75.6% less duff than unburned plots while plots that burned at an average of moderate severity had 26.3% less fine fuels and 77.0% less duff than unburned plots (Fig. 6; Table S9).

### Probability of torching

Results from the model with the lowest AICc score indicated that measurement timing (RI = 1.00) influenced the probability of torching ($\Delta AIC_c = 2.2$; Table S10). The mean probability of torching estimates per plot per measurement year was 39.0% pre-treatment, 2.0% 1-year post-treatment, and 3.6% in 2021 (Fig. 7).

## Discussion

Overall, we found that shaded fuel breaks reduced live basal area and retained larger-diameter trees immediately post-treatment, which persisted nearly 20 years after initial treatments were implemented. As predicted, both wildfire occurrence and the time since initial thinning treatments were included in our final model; however, these variables were only moderately associated with live basal area (marginal $R^2 = 0.25$) and live QMD (marginal $R^2 = 0.39$).

Observed changes in stand structure were in line with the stated fuel reduction objectives of the treatments, despite the different thinning prescriptions (Table 1) and operational resource constraints (e.g., Lydersen et al. 2019). It is worth noting that the observed negative treatment effects for three units (Table 1) were likely due to pre-treatment stand conditions (Table S1) being near or at treatment prescription limits resulting in minimal basal area removal, which was outweighed by basal area growth of the residual large trees in the post-treatment measurement.

The structures and fuel conditions created by these treatments are indicative of the ability for the combined application of mechanical thinning plus prescribed fire to enhance persistence of desired structural characteristics through repeated unplanned wildfires (Safford et al. 2012; Stevens et al. 2014; Murphy et al. 2021). The combination of these treatments followed by one or two reburns of low to moderate severity wildfire may provide mechanisms that enhance resistance by reducing understory fuel profiles (Steel et al. 2021) and resilience through maintaining low density forests (North et al. 2022).

Based on surface and ground fuel data collected in 2021, the observed influence of fire severity on fine fuels and duff is consistent with findings that wildfires of low severity can maintain low fuel loads initially created by shaded fuel breaks (Agee and Skinner 2005).

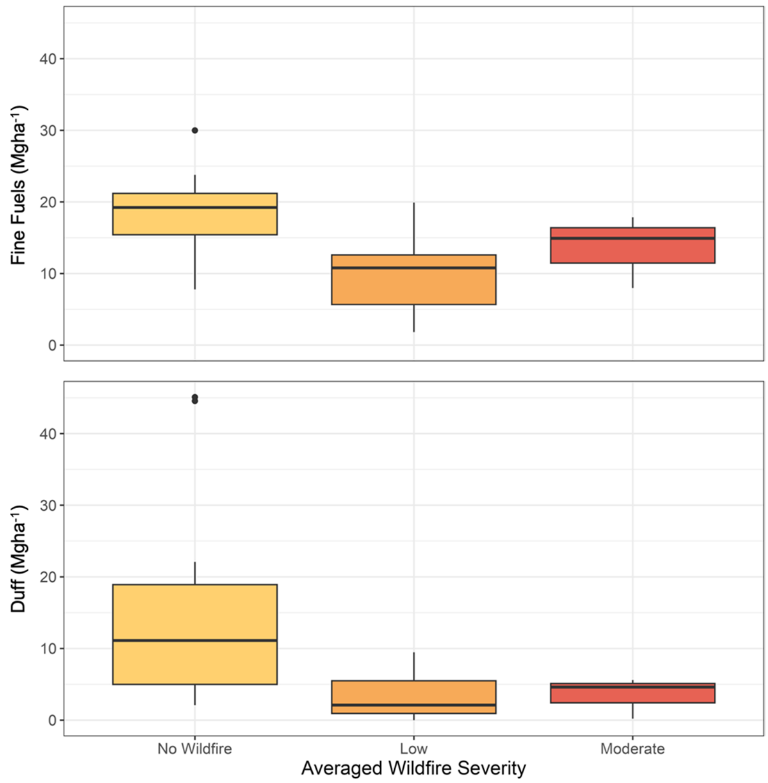


**Fig. 6** Averaged plot-level fine fuel estimates (Mgha$^{-1}$) and duff estimates (Mgha$^{-1}$) by averaged plot-level fire severity (i.e., no wildfire, low, moderate) for plots that burned in multiple wildfires. Fine fuels include 1-, 10-, and 100-h fuels and litter. No wildfire refers to plots that have not experienced wildfire since initial plot establishment in 2001

Averaged wildfire severity was moderately associated with fine fuels (marginal $R^2=0.38$) and duff (marginal $R^2=0.34$) at our sites. In plots that burned at moderate severity, greater fine fuel and coarse woody debris loads relative to plots that burned at lower severities (Table S9) can be attributed to deposition of foliage, branches, and eventually, boles of trees killed by moderate severity fire (Collins et al. 2018). However, it is worth restating that wildfire occurrence (0, 1, or 2 times) was included in our final model for coarse woody debris but had a weak connection to observed 2021 coarse woody debris loads (marginal $R^2=0.14$; Fig. 5). Greater duff loads in plots that had not experienced wildfire relative to those that burned at low and moderate severity are indicative of the accumulation of duff during longer periods of time post-treatment (Wright and Agee 2004; Keane et al. 2008). Duff loads may also be correlated with overstory characteristics such as snag basal area or canopy cover (Lydersen et al. 2015; Knapp et al. 2017; Fry et al. 2018); however, we did not measure these attributes continuously over time in our plots. Additionally, impacts of wildfire severity on fuel loads may be affected by differences in fuel treatment types (i.e., mechanical versus hand thin) in units exposed to wildfires as opposed to units with no wildfire. These differences in applied treatment types (i.e., mechanical versus hand thin) may reflect local differences in site characteristics, which can also influence wildfire severity (Lydersen et al. 2017).

Though wildfire occurrence was not included in our final model as predicted, our marginal $R^2$ value for P-Torch ($R^2=0.97$) indicated that measurement timing was strongly associated with P-Torch values at our sites. Oftentimes, the effective lifespan of fuel treatments depend on a number of factors including pre-treatment conditions, site productivity, and ability for the treatment to create desired conditions (Reinhardt et al. 2008). In the case of these treatments, not only were P-Torch values consistently lower over time post-treatment, but also initial discrepancies in unit treatment intensities (Table 1) did not negatively influence P-Torch values. Though we did not model future torching potential (i.e., beyond 2021), average P-Torch values remained well below pre-treatment estimates 20 years post-treatment (Fig. 7). It should be noted that P-Torch estimates are largely influenced by selected fuel models, which are inherently subject to assumptions by the modeler (Collins et al. 2010). However, we believe that the combination of our systematic approach

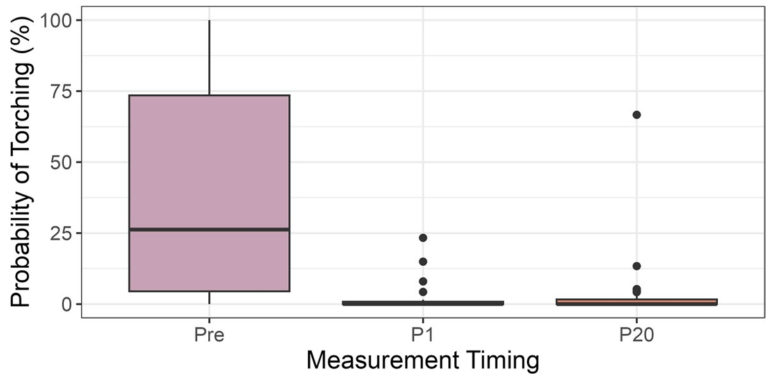


**Fig. 7** Average plot-level probability of torching (%) by measurement timing. Actual measurement years for these periods were: 2001 for pre-treatment (Pre), 2003–2009 for1-year post-treatment (P1), and 2021 for approximately 20-years post initial thinning treatments (P20)

to assigning models and verifying assigned models using local expert knowledge allowed for the reasonable selection of fuel models used to compute P-Torch values. Ultimately, results from this study provide an example of how fuel treatments in dry, pine-dominated forests can facilitate the use of managed wildfire in the future (Reinhardt et al. 2008; Stevens et al. 2014; Barros et al. 2018).

Though leveraging existing forest monitoring networks to conduct assessments of real-world treatment performance can provide valuable information to forest managers, understanding the potential limitations of these datasets is important for interpreting our findings. As previously mentioned, we used a monitoring dataset that was designed to quantify the immediate impacts of shaded fuel breaks (Cheng et al. 2016). Additionally, we were challenged to find a sample of plots within treatment units with long-term monitoring data that had also experienced the same gradient of wildfire exposure. While differences is productivity may have confounded our stand structure results, other studies of treatment efficacy across similar forest types demonstrated that treatment impacts outweigh potential impacts of local productivity on forest stand structure (Chiono et al. 2012). However, we attempted to address these limitations when adopting the original study design by employing a conservative and robust analytical framework. Currently, more empirical evidence of fuel treatment efficacy is needed to aid in the planning and implementation of treatments across large areas (Martinson and Omi 2013; Kalies and Yocom Kent 2016; McKinney et al. 2022). A critical component of adding to the information about treatment performance is the establishment of long-term monitoring plot networks, which can be used to understand the real-world impacts of varying treatment implementations, productivity gradients, and subsequent wildfires on forest stand conditions (Susskind et al. 2012).

## Conclusions

Our results suggest that the continued application of shaded fuel breaks can be a sound strategy for ensuring forest persistence through wildfire and may allow for the use of more ecologically beneficial fire across landscapes (Stephens et al. 2021). However, current capacities to maintain fuel treatments are often hindered by limits on funding and professional capacity as managers are tasked with implementing new treatments in unburned areas and rehabilitating recently burned areas (North et al. 2012; Hessburg et al. 2021). In the absence of follow-up maintenance treatments, wildfires of low to moderate severity can be used to maintain existing fuel treatments in dry, pine-dominated forests. Continuing to use existing long-term monitoring datasets to assess treatment efficacy can provide realistic outcomes to managers implementing multi-objective ecosystem management plans aimed at improving forest resilience to wildfires amplified by climate change.

**Abbreviations**

| | |
|---|---|
| AB | Antelope Border shaded fuel break |
| AICc | Akaike information criterion for smaller sample sizes |
| CWD | Coarse woody debris |
| DBH | Diameter-at-breast-height |
| HFQLG | Herger-Feinstein Quincy Library Group |
| P-Torch | Probability of torching |
| QMD | Quadratic mean diameter |
| RC | Red Clover shaded fuel break |

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-023-00187-2.

**Additional file 1: Table S1.** Summary of averaged live basal area ($m^2ha^{-1}$), live trees per hectare (TPH; trees $\geq$ 2.54 cm), and live quadratic mean diameter (QMD; cm) per unit per measurement timing. **Table S2.** Averaged plot-level wildfire severities for each plot that experienced one or two wildfires since initial plot establishment. One Antelope Border (AB) unit and all the Red Clover shaded fuel break did not experience any wildfire from 2001–2021. **Table S3.** Directional relationships of fixed effects included in the final models. A + indicates a positive relationship and a – indicates a negative relationship. **Table S4.** Model rankings and weights for live basal area. ΔAICc refers to the difference between a given model and the model with the lowest AICc score, which is bolded. All models included treatment unit as a random effect. **Table S5.** Model rankings and weights for live QMD. ΔAICc refers to the difference between a given model and the model with the lowest AICc score, which is bolded. All models included treatment unit as a random effect. **Table S6.** Model rankings and weights for CWD. ΔAICc refers to the difference between a given model and the model with the lowest AICc score, which is bolded. All models included treatment unit as a random effect. **Table S7.** Model rankings and weights for fine fuels. ΔAICc refers to the difference between a given model and the model with the lowest AICc score, which is bolded. All models included treatment unit as a random effect. **Table S8.** Model rankings and weights for duff. ΔAICc refers to the difference between a given model and the model with the lowest AICc score, which is bolded. All models included treatment unit as a random effect. **Table S9.** 2021 estimates of plot-level mean fine fuel, coarse woody debris (CWD), and ground fuel loads ($Mgha^{-1}$) by average wildfire severity. Fine fuels include 1-, 10-, 100-hour fuels and litter, CWD includes 1000-hour fuels, and duff. Average wildfire severity refers to the averaged plot-level fire severity for plots that burned in multiple wildfires. **Table S10.** Model rankings and weights for P-Torch. ΔAICc refers to the difference between a given model and the model with the lowest AICc score, which is bolded. All models included treatment unit as a random effect. **Figure S1.** Surface fuel model selection logic for Antelope Border and Red Clover shaded fuel break units pre-treatment (2001). Surface fuel models were selected from Scott and Burgan (2005) and are identified by code and by number. Each plot was assigned a high (H) and low (L) surface fuel model to capture the range of pre-treatment fuel conditions. Shrub cover (%) was divided into two categories based on average woody shrub height (tall ≥ 0.5 m and short < 0.5 m). Woody surface fuels ($Mgha^{-1}$) includes fine fuels (litter, 1-hour, 10-hour, and 100-hour fuels) and coarse woody debris (1000-h fuels).

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**Authors' contributions**
KEL: conceptualization, methodology, formal analysis, investigation, data curation, writing—original draft, writing—review and editing, funding acquisition. JJB: methodology, formal analysis, resources, writing—original draft, writing—review and editing, project administration, funding acquisition, supervision. RET: conceptualization, investigation, methodology, writing—review and editing, funding acquisition. CPD: data curation, investigation, project administration, writing—review and editing. SLS: writing—review and editing, supervision, funding acquisition. BMC: conceptualization, methodology, resources, writing—original draft, writing—review and editing, project administration, funding acquisition, supervision. The author(s) read and approved the final manuscript.

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**Availability of data and materials**
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

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

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## Publisher's Note