Journal of Environmental Management 395 (2025) 127866

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

The hidden variable: Impacts of human decision-making on prescribed fire outcomes

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ARTICLE INFO

Keywords:
Fire effects
Tree mortality
Crown scorch height
Crown base height
Fuel consumption
Fuel moisture content
Burn prescriptions

ABSTRACT

This study investigates the key drivers influencing prescribed fire effects across 16 sites in northern and central California, with particular emphasis on how operational decisions by fire practitioners shape burn outcomes. Data from the California Prescribed Fire Monitoring Program revealed that prescribed fires reduced total fuel loads by an average of 60 %, with greater consumption of postfrontal smoldering fuels (coarse fuels, 65 %) compared to frontline spreading fuels (fine fuels, 49.0 %).

Crown scorch height showed a strong relationship to crown base height (R^2 = 0.37–0.86), suggesting that practitioners use crown base height as a visual indicator to control fireline intensity and avoid crown damage. This relationship may partially explain fuel consumption patterns, as crown avoidance strategies can influence fire behavior and intensity. Additionally, we documented a compensatory relationship between live and dead fuel moisture content across burn seasons, indicating that practitioners strategically select burning windows that maintain fireline intensity within controllable parameters regardless of season.

Our findings demonstrate that human decisions fundamentally modify prescribed fire behavior to maintain safety parameters, often constraining outcomes to conservative ranges that may compromise treatment effectiveness. Understanding and accounting for these human factors is crucial to encouraging a more effective use of prescribed fires in the future. We recommend that future research explicitly include operational parameters and practitioner decision-making processes in assessing prescribed fire science, balancing safety considerations with goals for ecological restoration.

1. Introduction

Prescribed fire is an effective tool for forest restoration, wildfire risk reduction and biodiversity preservation (Stephens et al., 2024). Prescribed fire mimics low intensity wildfire in several ecological effects, such as reducing surface fuels, altering forest structure, creating canopy gaps, and influencing soil nutrient cycling (Agee and Skinner, 2005; Stephens et al., 2009). Many fire-adapted ecosystems rely on periodic fires to maintain their structure and function (Pausas and Keeley, 2009).

Wildfires and prescribed fires both spread through the same physical mechanisms—combustion driven by fuel, weather, and topography (Byram, 1959)— but their outcomes diverge sharply due to differences in moisture conditions, fuel structure, and human control. Wildfires typically occur under low live and dead fuel moisture, with intense vertical flames that often exceed crown base height (Cruz and Alexander, 2010), leading to canopy scorch and full consumption of both fine and coarse fuels (Alexander and Cruz, 2012b; Nolan et al., 2022). These conditions result in severe ecological disruption shaped by extreme and unmanaged environments. However, wildfires can also burn under diminished burning conditions, creating low-intensity burn scars (Lesmeister et al., 2019). In contrast, prescribed fires are intentionally ignited under carefully selected conditions that favor low-intensity

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https://doi.org/10.1016/j.jenvman.2025.127866
Received 5 August 2025; Received in revised form 19 October 2025; Accepted 30 October 2025
Available online 1 November 2025
0301-4797/

surface burns (Ryan et al., 2013) to reproduce natural low-intensity wildfire regimes. Human decisions in prescribed burning guide ignition timing and spatial patterns, fuel targeting, and containment strategies, enabling prescribed fires to reduce fine fuel loads while preserving canopy structure and minimizing ecological damage (Fernandes and Botelho, 2003; Molina et al., 2022). Though governed by the same fire physics, prescribed fire transforms fire from threat to tool, by interrupting fuel continuity and lowering the risk of future high-intensity wildfires (Agee and Skinner, 2005).

However, prescribed fires implementation faces significant challenges including uncertain outcomes, air quality regulations, funding shortages, personnel limitations, narrow burn windows, liability concerns, and complex environmental regulations (Quinn-Davidson and Varner, 2011). The greatest challenge and uncertainty source stems from decades of fire suppression and reduced fire frequency, which has led to excessive fuel accumulations in many ecosystems (Steel et al., 2015). In such fuel-loaded conditions, human driven prescribed fires regimes, intended to restore fire's ecological role, may burn with unintended intensity, potentially causing excessive tree mortality, soil damage, or fire escape risks (Hiers et al., 2020).

Research on prescribed fire effects is needed to reduce uncertainty and overcome challenges. However, such research has largely adopted approaches, tools, and metrics from wildfire science, despite fundamental differences in their nature and application. Uncertainty about prescribed fires outcomes persists due to the complex and variable nature of environmental and practitioners decisions (Hiers et al., 2020). While fuel availability, structure, topography, and timeframe influence fire behavior in prescribed fire and wildfire, a critical distinction exists: in prescribed fire, firing patterns determine fireline intensity (FLI) through ignition line spacing and direction relative to wind and slope. Closer ignition lines produce lower intensity; wider spacing increases intensity (Byram, 1959; Wade and Lunsford, 1989). As a result, prescribed fires will result in fire behavior and fire effects- —rate of spread ($m \cdot s^{-1}$), flame length (m), scorch height (m), FLI ($kW \cdot m^{-1}$)— modulated by the ignition crew, whereas a similar low intensity wildfire in the same area would exhibit different effects modulated by fire front alignment microtopography, weather and fuel pockets (Byram, 1959).

To support the prescribed fire's ecological role and bridge the gap with wildfire research, prescribed fire science requires approaches that center human decision-making, yet most research has relied on wildfire frameworks that ignore active management during operations (Hiers et al., 2020). Existing simulation tools (e.g., Behave, FOFEM, FFE-FVS) were developed for wildfire behavior and cannot adequately assess the complex fire behavior arising from prescribed fire ignition patterns. The California Prescribed Fire Monitoring Program was established in 2019 to address this gap through a permanent and extensive network of monitoring plots that systematically quantifies prescribed fire ecological effects and smoke impacts (Safford et al., 2023). The program aims to better inform fire practitioners about the effects and effectiveness of their burn prescriptions and tactics (Domènech et al., 2024).

During prescribed fires, practitioners make real-time adjustments using visual indicators. These include flame height, crown base height, tree density, weather changes, and time of day (National Wildfire Coordinating Group (NWCG), 2025). Live and dead fuel moisture content affect the availability of the fuel for ignition (Resco de Dios et al., 2015), and are used to determine prescription windows, the range of environmental conditions under which burns can be safely performed while meeting smoke management objectives.

Crown scorch height measured shortly after fire, serves as a practical field indicator of FLI and tree damage. Defined as the average height to which foliage is killed by fire (Alexander et al., 2019), it manifests as a yellowish-brown needle discoloration resulting from lethal temperatures (Molina et al., 2022). Crown scorch extent indicates physiological impacts including reduced growth, weakened defenses, and increased mortality (Varner et al., 2021), making it valuable for assessing prescribed fire objectives and developing predictive models relating crown base height to FLI (Van Wagner, 1973). Its visibility and ease of measurement make it the primary metric practitioners and researchers use to evaluate fire effects.

Our research aims to characterize the drivers of fuel consumption and crown scorch heights in prescribed fires, and to provide evidence that human decision-making fundamentally influences burn outcomes. We evaluated prescribed fire effects on fuel consumption across large statewide plot network and examined how practitioner decisions shape these outcomes. While the effectiveness of prescribed burning in reducing fire hazards has been extensively studied (Ritter et al., 2023; Vaillant et al., 2009), few studies have examined how human decision-making processes influence fire patterns and burn performance (Bonner et al., 2024).

We hypothesized that human choices significantly influence prescribed fire outcomes, specifically that fire practitioners adopt conservative approaches that prioritize safety and control over maximum fuel reduction. If practitioners are risk-averse during implementation, we would expect to see: (1) crown scorch heights closely aligning with crown base heights, indicating controlled FLI to minimize tree damage; (2) a compensatory relationship between live and dead fuel moisture content (DFMC) across burn seasons, suggesting strategic burn window selection; and (3) consistent fuel consumption patterns reflecting human intervention (from points 1 and 2 above) rather than just environmental factors. In our study, we did not measure the firing pattern directly; instead, we used scorch height on trees as a proxy. By recording the scorch height, we can infer the FLI applied by the firing pattern.

2. Methods

2.1. Study location

The study was undertaken at 16 sites (375 total plots, from 2 to 75 per site) across northern and central California, sampled by the California Prescribed Fire Monitoring Program (Safford et al., 2023). Within each delineated burn unit, a stratified random sampling approach was employed to establish vegetation monitoring plots. Plot centers were systematically located on the vertices of a grid, with stratification based on vegetation type and previous treatment history (when applicable). A buffer zone of 50 m was incorporated to mitigate edge effects and proximity to roads.

Monitoring plots spanned a variety of forest types, including mixed conifer, "eastside pine" (mixed *Pinus ponderosa* and *P. jeffreyi*), coastal redwoods, and montane hardwood forests, as well as oak woodlands. Mean annual precipitation at the sites ranges from 458 to 1666 mm. Mean minimum temperature in January ranges from −2.1 to 10.1 °C, and mean maximum temperature in July ranges from 13.2 to 22.4 °C (Fig. 1A and B). Altitude ranges from 68 to 2492 m (Supplementary methods). Tree species include ponderosa pine (*Pinus ponderosa* Laws), Jeffrey pine (*P. jeffreyi* Grev. & Balf.), white fir (*Abies concolor* Gord. & Glend), sugar pine (*Pinus lambertiana* Dougl.), incense-cedar (*Calocedrus decurrens* (Torr.) Floren.), red fir (*A. magnifica* A. Murray bis), California laurel (*Umbellularia californica* (Hook. & Arn.) Nutt.), redwood (*Sequoia sempervirens* (Lamb. ex D. Don) Endl.), coast live oak (*Quecus agrifolia* Née), interior live oak (*Quercus wislizeni* A. DC.), and California black oak (*Quercus kelloggii* Newb.).

2.2. Vegetation measurements

Within each site, we established 0.04 ha permanent circular plots; field data were collected using a modified version of the USDA Forest Service common stand exam (USDA Forest Service, 2012).

Tree species, status (live or dead), DBH, total height, and crown base height were recorded for all trees with a DBH greater than 7.6 cm before and one year after prescribed fire treatments. We recorded crown scorch height 2 weeks to 2 months after prescribed fire treatment as the distance between the ground surface and the crown scorch height, with

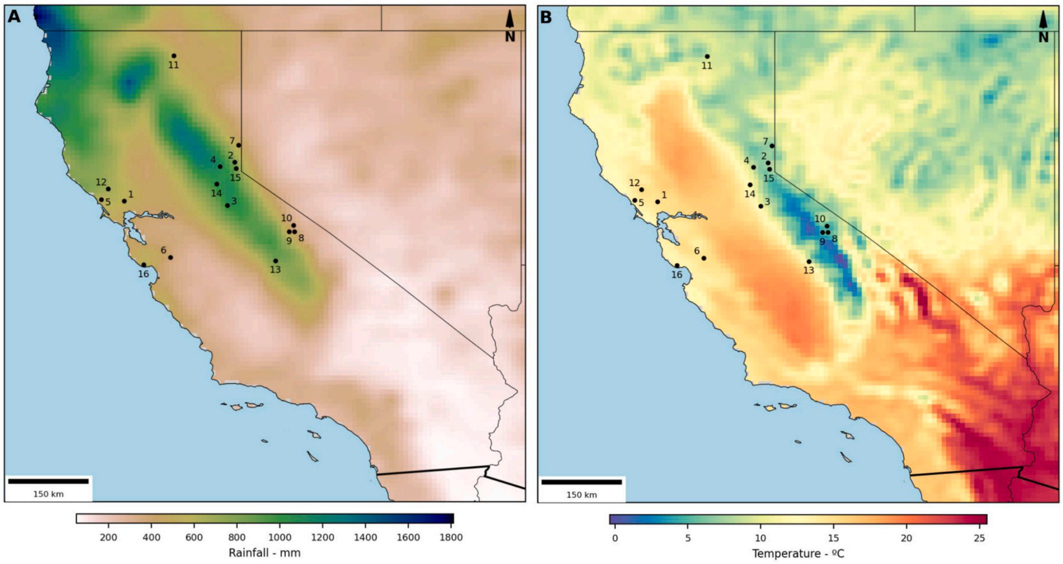

Fig. 1. Site locations. A. Mean annual precipitation (mm) for the last 30 years (1994–2024). B. Mean annual temperature (°C) for the last 30 years (1994–2024). Sources: A and B, ERA5-Land monthly averaged data from (1994–2024; Site names: 1 Bouverie, 2 Burton creek, 3 Calaveras Big trees North, 4 French Meadows, 5 Grove of the Old Trees, 6 H Coe, 7 Humboldt Dog Valley, 8 Inyo Antelope, 9 Inyo Dry Creek, 10 Inyo SpringsFire, 11 Modoc Rush, 12 Rio Lindo, 13 Shaver Lake South, 14 Sly Park, Fire, 15 Sugar Pine, 16 Wilder Ranch.

scorch height being the mean of measures of both the highest and lowest scorch height on the tree in question.

2.3. Ground and surface fuel characteristics

Surface and ground fuels were sampled at 4 compass azimuths (N, S, E, and W from the plot center) using the line-intercept method (Brown et al., 1982) before, immediately after, and 1 year after prescribed fire treatments. Surface fuels are dead woody material lying on the ground surface, while ground fuels are leaf or needle litter and duff, which are found below surface fuels and comprise the combustible organics found at the top of the soil pedon (Brown et al., 1982). Surface fuels: 1hr (0–0.64 cm diameter) and 10hr (0.64–2.54 cm) fuels were sampled from 0 to 2 m, while 100hr (2.54–7.62 cm) fuels were sampled from 0 to 4 m, and coarse woody debris (>7.64 cm; aka 1000hr fuels) from 0 to 11.4 m on each transect. Ground fuels: duff and litter depth (cm) were measured at 2 points along each transect.

Surface and ground fuel loads were calculated using appropriate equations developed for California forests (Van Wagdendonk et al., 1996). Coefficients for calculating surface and ground fuel loads were arithmetically weighted by the basal area fraction to produce accurate and precise estimates of ground and surface fuel loads using the Rfuel package (Foster et al., 2018). Fuel consumption (%) per each fuel category and for total fuel was calculated as prefire fuel load minus postfire fuel load, divided by prefire fuel load.

2.4. Prescribed fire treatments

All sites were treated by prescribed fire between 2019 and 2023, with the primary objective of fuel reduction and ecosystem restoration. Prescribed fires occurred either in spring or fall, depending on the weather, fuel condition, and available personnel. The Inyo Springs Fire, a managed wildfire with extensive prescribed fire intervention, was conducted during the summer months. Landowners included USDA Forest Service, California State Parks, and The Nature Conservancy, among others, and the burned surface area ranged from 2.3 to 234.2 ha (2676.8 ha in the Inyo Springs Fire) (Supplementary Methods).

2.5. Fuel moisture content estimates

We estimated dead fuel moisture content (DFMC) following previously published and validated methods for California based on gridded vapor pressure deficit (VPD) data (Nolan et al., 2016). VPD was estimated from 2m-temperature and 2m-dew temperature from the ERA5-Land Dataset, for the month of each prescribed fire (Muñoz-Sabater et al., 2021).

Live fuel moisture content (LFMC) was estimated with the LFMC-RF remotely sensed model previously developed for the Mediterranean basin (Cunill Camprubí et al., 2022), calculated as the monthly mean. The method is largely based on land surface temperature (LST) and different spectral indices from the 6.1 MODIS data. Data were retrieved through Google Earth Engine. We trained and validated LFMC-RF using the LFMC data for California based on the average LFMC for each of the different woody species in each site within the Globe-LFMC 2.0 dataset (Yebra et al., 2024), as described in the Supplementary Methods.

2.6. Data analyses

Crown scorch height analyses utilized individual tree measurements ($n = 2275$ trees), while fuel consumption analyses were conducted at the plot level ($n = 375$ plots) since fuel load measurements represent plot-scale attributes.

To determine the effect of prescribed fire on surface fuel loading, we compared surface fuel loads for each fuel type (1hr, 10hr, 100hr, coarse woody debris (CWD), duff, and litter) before and after prescribed fire. Normality and homoscedasticity was assessed from the residual plots. Due to the lack of homoscedasticity across all fuel categories, Kruskal-Wallis tests were performed to identify differences before and after prescribed fire (Supplementary Methods).

To examine the relationship between live and dead fuel moisture content across burning seasons, we conducted a bivariate density analysis. LFMC and DFMC daily values for each plot were categorized by burn season (spring, summer, fall) based on the burn date. The overall relationship between DFMC and LFMC was quantified using Pearson correlation analysis, and a linear regression line was fitted to visualize the general trend across all seasons.

We developed a random forest (RF) model (Breiman, 2001) to assess the relative influences of multiple factors on total fuel consumption, with the goal of describing processes, rather than predicting responses. We examined model accuracy from the mean squared residual error and the percentage of the variance explained by the model. The model incorporated terrain variables (aspect, elevation, and slope), weather conditions (Aridity Index), fire prescription parameters (burning time and fuel moisture content), fire behavior metrics (crown scorch height), and prefire stand attributes (prefire fuel load in t ha^{-1} and tree density in trees ha^{-1}). Long-term climatic conditions were characterized using the Aridity Index (AI), calculated as the ratio of mean annual precipitation to potential evapotranspiration (P/PET), following the UNEP classification scheme (United Nations Environment Programme (UNEP), 1992; Zomer et al., 2022). Crown scorch height served as a proxy for fireline intensity (FLI), a well-established metric in prescribed fire modeling systems such as BEHAVE for predicting fire effects (Van Wagner, 1973). Prior to model development, we assessed potential multicollinearity using Pearson's correlation coefficients among variables. Following previously published recommendations (Dormann et al., 2013), we used the threshold of $r > |0.70|$ as the value above which collinearity could bias model estimation, but no r value was higher than 0.7.

We used the default values in R's random forest library (Liaw and Wiener, 2002). That is, the number of variables tried at each split was the number of predictors divided by 3, and 500 trees were built. The error rate of the model was then used to tune the model. We additionally assessed variable importance and conducted partial dependence analyses to characterize the dependence of model predictions on important predictor variables.

We developed a second RF model to examine the relative influence of terrain (aspect, elevation, and slope), weather (Aridity Index), fire prescriptions (burning time, fuel moisture content), prefire tree density, burn unit, and species on crown scorch height. The model development followed the same methodology as described above, including multicollinearity assessment using Pearson's correlation coefficient with a threshold of 0.70 (Dormann et al., 2013).

3. Results

3.1. Fuel consumption

We studied prescribed fire effects on fuel loading in the ground and surface strata. Total fuel loading (including 1hr, 10hr, 100hr, CWD, duff, and litter) decreased from a mean of 113.7 (±4.7; mean ± SE) t ha^{-1} before prescribed fires to a mean of 45.1 (±3.2) t ha^{-1} 1 year after,

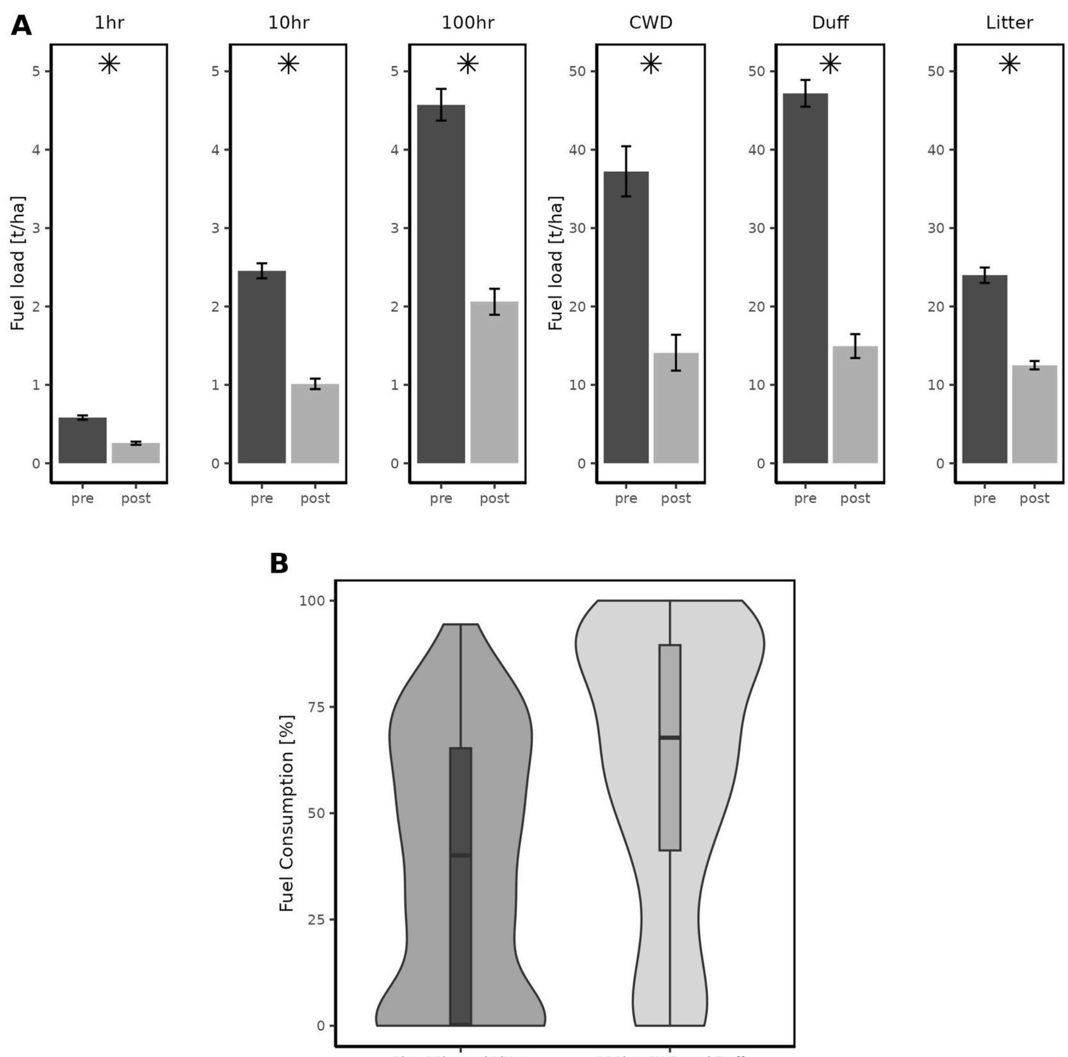

Fig. 2. Prescribed fire effects on fuel load and consumption. A. Prefire and postfire fuel load by fuel type (1hr, 10hr, 100hr, CWD, duff, and litter). Bar values are the mean fuel loading values (t/ha) and ±1 standard error. Stars indicate a significant difference between prefire and postfire fuel load estimates for each fuel load type, p-values were <0.0001 (Supplementary Methods, Table S2). There were significant differences between prefire and postfire fuel loads in all fuel types. **B. Effects of prescribed fires on fuel consumption (%)**. Violin plots showing the distribution of fuel consumption (%) for fine fuels (1hr, 10hr, and litter), and coarse fuels (100hr, CWD, and duff). Box plots within each violin show the median (center line), interquartile range (box), and whiskers extending to 1.5 × IQR.

varying across sites. Prefire fuel load exhibited a right-skewed distribution with a mean of 113.7 t ha^{-1} but a lower median of 98.9 t ha^{-1} (Quantile 25 %-Quantile 75 % = 51.4–160.3 t ha^{-1}), indicating substantial site-to-site heterogeneity (Supplementary methods).

Prescribed fire reduced the loads of all fuel types significantly (p-values <0.0001) (Fig. 2A). The load of fuels that primarily contribute to fire spread— 1hr, 10hr, and litter—decreased from a mean of 26.8 t ha^{-1} to 13.7 t ha^{-1} (49 % of consumption). In contrast, the reduction of fuels that typically burn after the initial frontline spread, such as 100hr, CWD, and duff, experienced a more significant reduction, from a mean of 88.1 to 30.9 t ha^{-1}, with a fuel consumption of 65 % (Fig. 2B). Immediately postfire, consumption patterns showed less divergence between fuel categories (68 % for 1hr, 10hr, and litter vs. 70 % for 100hr, CWD, and duff; Supplementary methods).

The random forest model yielded a mean squared residual (MSR) of 411.6 and explained 51.5 % of the variance in total fuel consumption. Dead fuel moisture content (DFMC) and burn month were the two most important variables influencing fuel consumption, crown scorch height also had an important relationship to consumption (Fig. 3A).

The partial dependence plots (Fig. 3B) show that dead fuel moisture content has a threshold effect around 15 %, above which the model's average probability of fuel consumption decreases considerably (from approximately 56 %–44 %). Seasonally, burns conducted in June and September through December achieved higher fuel consumption compared to those in January and May. No prescribed burns were performed in the other months. Crown scorch height showed a gradual positive relationship, with values from 0.5 to 15 m corresponding to fuel consumption increases from 48 % to 56 % (Fig. 3C).

3.2. Live and dead fuel moisture content

The two most important factors affecting fuel consumption were DFMC and the month of the burn (Fig. 3A). Burn timing is strategically chosen based on fuel moisture, fuel availability, and spread potential, among other factors. As a key indicator of human management decisions, burn timing, along with the firing pattern, exerts an overarching influence on the fire effects.

The correlation between LFMC and DFMC at the time of burning was

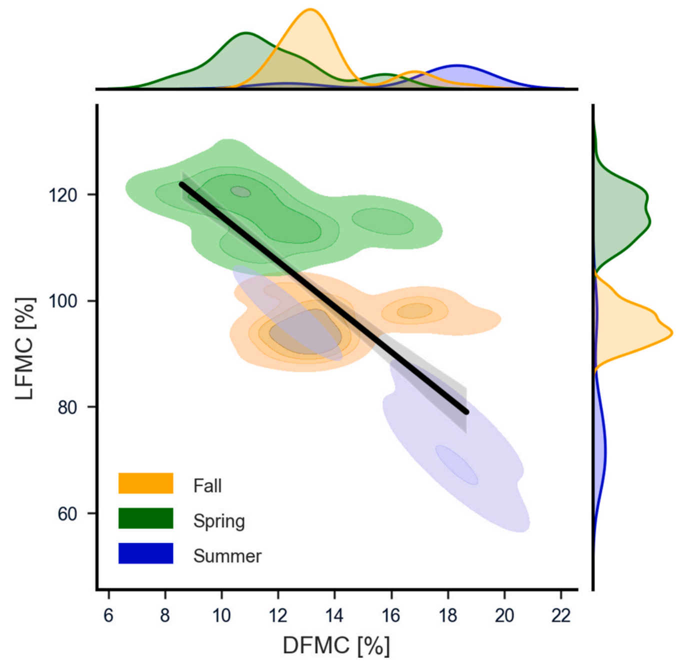

Fig. 4. Relationship between dead fuel moisture content and live fuel moisture content during the burn for each plot and across seasons. Density contours show the distribution of dead and live fuel moisture values for prescribed fires conducted in different seasons (Fall = orange, Spring = green, Summer = blue). The black line indicates the results of linear fitting that shades the 95 % CI, and shows the overall negative relationship between dead and live fuel moisture content (r = −0.56). Marginal density plots (top and right) show the distribution of each variable across all seasons.

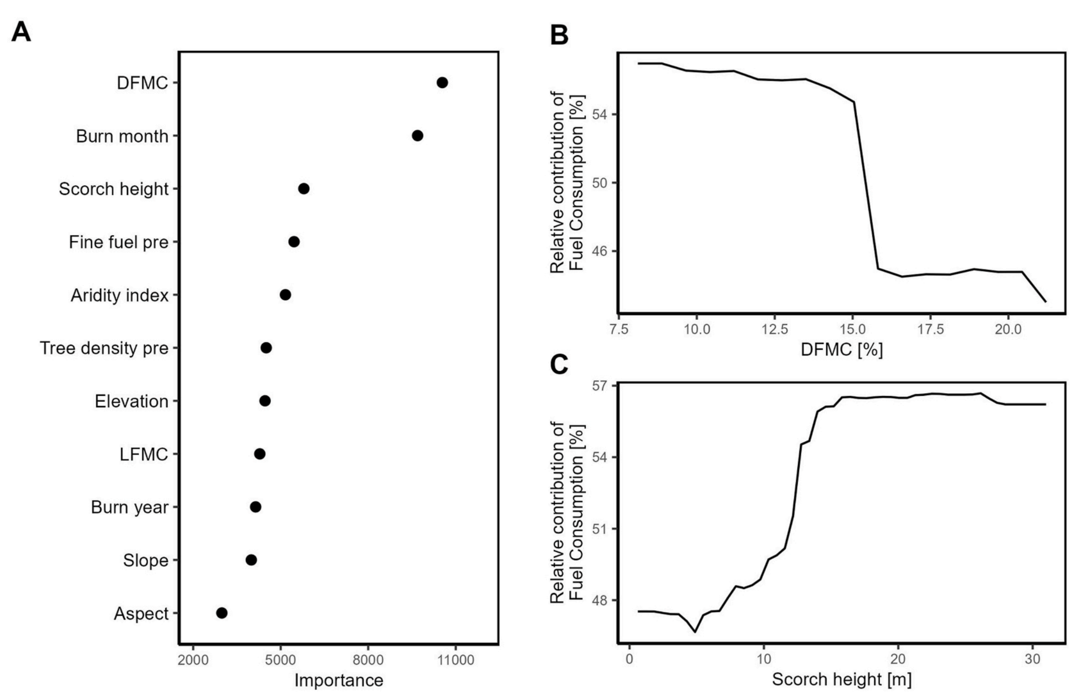

Fig. 3. Fuel consumption prediction. A. Variable importance plot for a balanced random forest model predicting total fuel consumption. Dead fuel moisture content, burn month, and crown scorch height played a significant role in determining the amount of fuel consumed in a burn. **Partial dependence plots show the probability of fuel load consumption for different levels of (B) dead fuel moisture content (DFMC) and (C) crown scorch height**. DFMC shows a threshold effect around 15 %, while scorch height shows a gradual positive relationship up to approximately 15 m.

r = −0.56 (Fig. 4). Spring burns with high LFMC (>110 % in spring) tend to occur when DFMC is relatively low (<12 %). In the fall and summer, burns tend to occur with relatively low LFMC and a higher DFMC.

3.3. Canopy scorch height and mortality

Crown scorch height (SH) was the third most important factor driving fuel consumption, and it serves as a critical indicator of fire effects on tree damage that is actively managed and controlled by fire practitioners who often seek to minimize torching in large trees. To further understand its significance, we analyzed relationships between mean tree height (TH), crown scorch height (SH), and crown base height (CBH) across diameter classes (Fig. 5A).

Our findings revealed that SH maintains a consistent relationship with CBH independent of TH across all diameter classes. The constant relationship between CBH and SH had a greater effect on small-diameter trees, which showed a high sensitivity to scorching. For example, in the diameter class of 10–20 cm, CBH was recorded at 3.3 m (SE = 0.1), and SH was 5.6 m (SE = 0.2). In contrast, for trees within the 50–70 cm diameter class, CBH measured 8.8 m (SE = 0.3) while SH was 13.8 m (SE = 0.4). For all diameter classes, the average difference between SH and CBH was 4.2 m (ranging from 2.2 to 7.5 m), while the average crown height (difference between TH and CBH) was 13.6 m (ranging from 3.6 to 29.8 m). Overall, trees with diameters less than 30 cm had 46–56 % of their crown scorched, compared to only 23–36 % for trees exceeding 30 cm in diameter.

This differential impact aligns with the higher mortality rates observed in smaller diameter classes. As seen in Fig. 5B, mortality rates were higher in smaller-diameter trees (7.6–20 cm) at 47.2 % (SE = 3.3) compared to larger-diameter trees (>80 cm), which had a mortality rate of only 6.0 % (SE = 2.1).

3.4. Canopy scorch height variation between species

Species-specific responses further illustrate how uniform firing patterns produce varied ecological outcomes. We examined two common conifer forest species – white fir (ABICON) and Jeffrey pine (PINJEF) – and analyzed TH, SH, and CBH across diameter classes (Fig. 5A).

Both species presented similar overall crown scorch proportions (36.2 % ABICON vs 36.1 % PINJEF), but when examining each diameter class in detail, distinct patterns emerged between species. At lower DBH classes, ABICON showed higher canopy scorch proportions (76.6 % for 7.6–10 cm DBH and 52.7 % for 10–20 cm DBH) compared to PINJEF (39.8 % for 7.6–10 cm DBH and 46.2 % for 10–20 cm DBH). From 30 cm DBH and above, the proportions were similar (26.4 %–44.9 % for ABICON, 32.2 %–50.8 % for PINJEF). These measurements reveal a critical threshold: beginning at 30 cm diameter, both species showed similar scorch height vulnerability, which makes selective firing challenging in prescribed fire operations.

We examined multiple factors for predicting scorch height. The

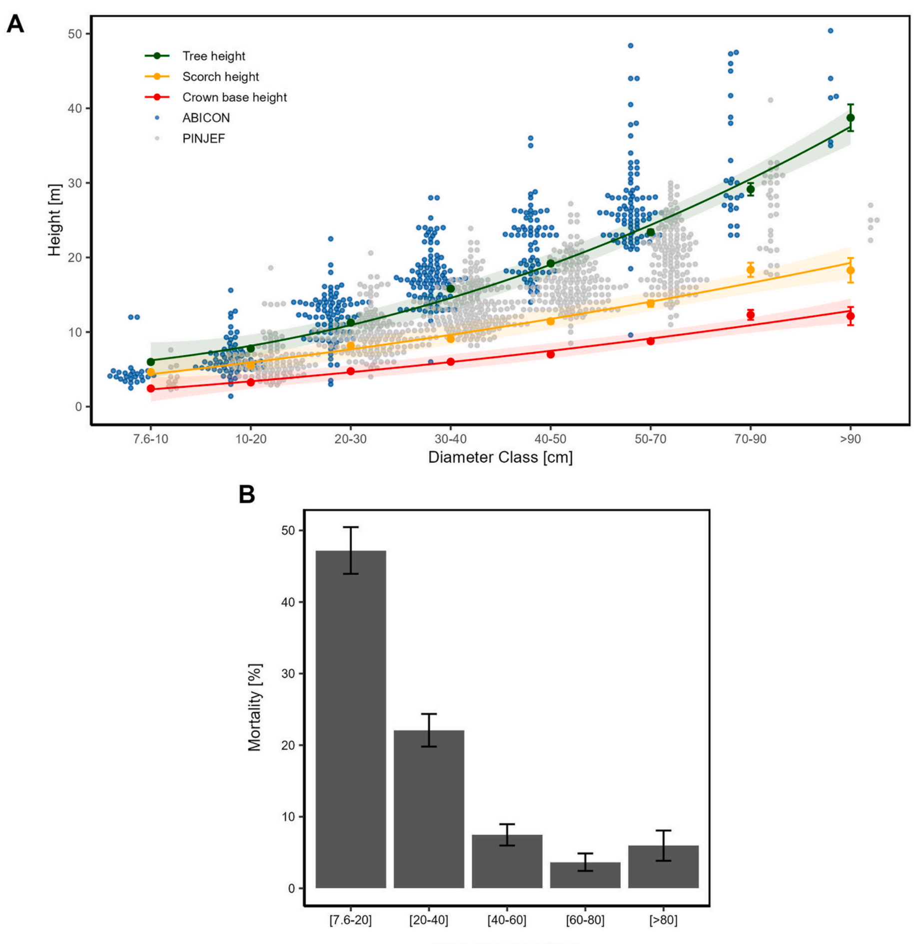

Fig. 5. Effects of prescribed fires on crown scorch height (m) and on tree mortality (%). A. Proportional effects of prescribed fire on crown scorch height (m) by tree diameter. Mean Tree height (green), Crown scorch height (orange), and Crown base height (red) are plotted by diameter class, with ±1 standard error. Quadratic regression fits are shown with 95 % confidence intervals. Individual tree heights for *Abies concolor* (ABICON) (blue) and *Pinus jeffryii* (PINJEF) (gray) species are plotted as dots. **B. Tree mortality (%) by diameter class**. Mean Tree Mortality (%) by diameter class with ±1 standard error, calculated as the number of dead trees in each diameter class divided by the total number of dead trees across all diameter classes.

random forest model achieved a mean squared residual (MSR) of 17.7 and explained 66.5 % of the variance in scorch height. CBH emerged as the dominant predictor (Fig. 6A), accounting for 29.5 % of the variance, followed by burn unit as the second most influential factor (12.8 % of the variance). Partial dependence plots illustrated that as CBH increased from 0.5 to 30 m, the relative contribution of the crown scorch height increased substantially from 6 % to 15 %, reinforcing the strong relationship between these variables across operational conditions (Fig. 6B).

Finally, to identify reliable field indicators for predicting crown scorch height, we analyzed relationships between crown scorch height and three easily observable variables: crown base height (Fig. 6C), tree height, and diameter at breast height (Supplementary Methods). We examined these relationships for different tree species individually. We found a strong correlation between SH and CBH for most species. CBH was a good predictor of the resulting crown scorch height for species such as PINLAM ($R^2 = 0.86$), CALDEC ($R^2 = 0.77$), PINJEF ($R^2 = 0.59$), SEQSEM ($R^2 = 0.63$), and ABICON ($R^2 = 0.57$). In contrast, TH and DBH exhibited lower correlation values for all species analyzed, with TH R^2 values ranging from 0.07 to 0.58, and DBH R^2 values ranging from 0.00 to 0.45. Additionally, all analyzed species showed a consistent linear relationship between SH and CBH, unlike the varying relationships observed with TH or DBH, which differed significantly among species.

4. Discussion

4.1. Fuel consumption patterns

Our findings demonstrate that prescribed fires in California forests effectively reduce fuel loads but with varying efficiency across fuel types. Differences in prefire and postfire fuel load were observed across study sites, aligning with prior research in Sierra Nevada mixed conifer, coastal redwood, and oak woodland ecosystems (Innes et al., 2006; North et al., 2007; Stephens et al., 2009). Sites containing redwoods and sequoias—such as Calaveras, French Meadows, Grove Old Trees, and Wilder Ranch—had higher mean fuel loads due to large, downed trees. These findings are consistent with earlier studies reporting prefire fuel loads in redwood forests of 252–619 t ha^{-1} (Busing and Fujimori, 2002; Norman et al., 2009).

Our data reveals two critical temporal dynamics. On the one hand, the proportion of coarse fuels and fine fuels consumed immediately postfire, was relatively similar (70 % vs 68 %, respectively). On the other hand, when we analyzed consumption 1yr postfire, after scorched foliage had fallen, the pattern became even more pronounced: coarse fuel reduction (65 %) substantially exceeded fine fuel reduction (49 %) (Fig. 2). It is worth noting that, compared to wildfires where there is high fine fuel consumption (>90 %) and few heavy fuel load consumption (<25 %) (Finney et al., 2021; McCarley et al., 2022), our prescribed fires consumed a disproportionately higher fraction of coarse fuels, a signature of conservative conditions favoring smoldering combustion over flaming combustion.

While practitioners can actively manage spreading surface fuels through real-time ignition adjustments and visual flame assessment, smoldering combustion continues largely beyond direct control, persisting after the primary burn operations cease. This prolonged smoldering increases tree mortality through extended heat exposure (Varner et al., 2021), damages soil properties, and produces uncontrollable smoke emissions that limit prescribed fire application.

These observations demonstrate that prescribed fires require fundamentally different evaluation frameworks than wildfires. The conservative nature of prescribed fires, combined with the homogeneous patterns of fire spread and intensity we observed across plots, amplifies these differences when compared to the inherent patchiness and natural variability characteristic of even low-intensity wildfire effects, and challenges the validity of applying wildfire-based models to managed burning operations.

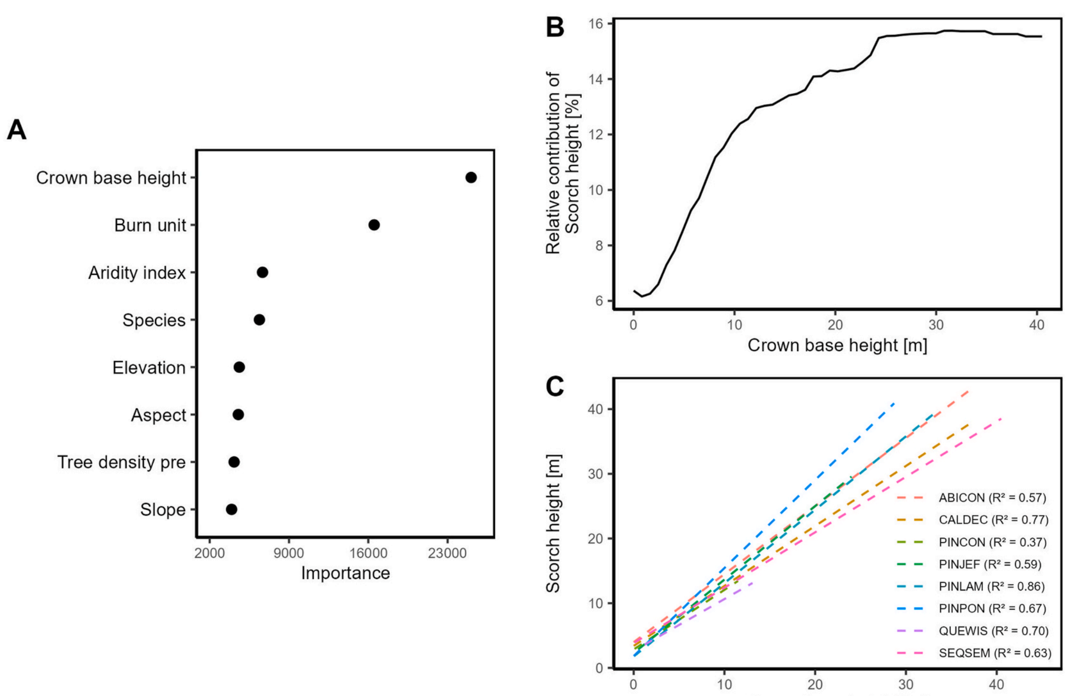

Fig. 6. Crown scorch height prediction. **A. Variable importance for a balanced random forest model predicting crown scorch height**. Crown base height shows the highest importance, followed by burn unit among the environmental and forest structure predictors. **B. Partial dependence plot. Partial dependence plot showing the probability of crown scorch height for different values of crown base height. C. Crown base height versus scorch height relationships for eight tree species.** Dashed lines show linear regressions with R^2 values. Crown base height showed the best correlation in a single model across all species compared with Tree height and Diameter at breast height (Supplementary Methods).

4.2. Intensity control by fire crews in prescribed fires

Our results highlight the critical role of human decision-making in prescribed fire outcomes (Fig. 3). Dead fuel moisture content and burn month emerged as primary predictors of fuel consumption, and together with crown scorch height explained 23.2 % of the total variance observed. All three factors are directly influenced by human decisions regarding burn timing and firing patterns. This research supports existing knowledge that burning techniques can be adjusted to maintain lower flame lengths, thereby reducing crown scorch (Wade and Lunsford, 1989).

The seasonal timing of the burns illustrates a sophisticated approach to intensity management (Fig. 4). Our data revealed an interesting compensatory relationship between live and dead fuel moisture content. Burns conducted in spring occurred under conditions of low dead fuel moisture but high live fuel moisture, while fall burns featured the opposite pattern. This suggests that practitioners deliberately select burning windows that maintain FLI within a safe, controllable range regardless of season.

This strategic fuel moisture selection contrasts with wildfires, which predominantly occur during seasonal windows when vegetation and atmospheric conditions simultaneously favor fire spread. California's most destructive wildfires have occurred during late summer and fall when both live and dead fuel moisture reaches annual minims following extended drought periods (Williams et al., 2019).

A compelling finding from the California Prescribed Fire Monitoring Program challenges conventional fire behavior models. In our prescribed fires, crown scorch height remains remarkably consistent with crown base height across tree diameter classes, suggesting that burn practitioners actively adapt firing techniques to the mean crown base height of the stand. This observed pattern contradicts traditional wildfire behavior models, which assume fire spread from an ignition point to a steady state (Rothermel, 1972) that persists under stable conditions. In prescribed fires, practitioners intentionally disrupt this steady state progression, using firing patterns specifically designed to maintain fire behavior within prescribed thresholds that balance control objectives with desired ecological effects. This human-driven modulation explains the near-constant crown scorch height we observed despite variations in tree diameter (Fig. 5). Crown scorch height is especially sensitive to FLI (Alexander and Cruz, 2012a), creating high spatial heterogeneity in natural fires even at low intensities. This high sensitivity is not observed in our prescribed fires, thus reinforcing the homogenizing effect of human-dominated firing patterns. The implications of this finding are significant for both fire behavior modeling and prescribed fire planning, suggesting that human factors fundamentally alter fire behavior in ways not captured by conventional models.

4.3. Crown scorch height as an operational indicator

Crown scorch height results from buoyant heat flux on tree crowns, with flame height and FLI as primary drivers (Byram, 1959). While taller trees can experience greater absolute scorch heights, shorter trees and those with lower crown base heights are disproportionately affected because their entire crown volume is positioned near ground level where lethal temperatures persist (Van Wagner, 1973). This proximity to the heat source increases the likelihood of complete crown scorch and tree mortality in smaller trees, even when absolute scorch heights are similar (Varner et al., 2021).

Crown base height emerged as the strongest predictor of crown scorch height, accounting for 29.5 % of the total variance and demonstrating a consistent linear relationship across species. This strong correlation provides practitioners with a reliable visual indicator for adjusting firing patterns in real-time. Our findings suggest that burn bosses likely use crown base height as a key reference point when determining appropriate FLI levels during prescribed burns, supporting the observations of Fernandes and Botelho (2003) regarding practitioner reliance on visual indicators.

The differential impacts of crown scorch across diameter classes align with the observed mortality patterns, with smaller trees (<30 cm diameter) experiencing 46–56 % crown scorch and corresponding higher mortality rates (47.2 % for 7.6–20 cm trees), compared to larger trees (>80 cm) with only 23–36 % crown scorch and 6 % mortality. This size-dependent vulnerability reflects the combined effects of thinner bark, lower crowns, higher stand density, and competitive disadvantages of smaller trees (Knapp et al., 2021; Varner et al., 2021).

4.4. Species-specific responses and management implications

The differential effects of prescribed fire on tree species within mixed conifer stands further illustrate how universal firing patterns can produce varied ecological outcomes. For example, a prescribed burn in a mixed stand of ABICON and PINJEF will be applied with a modulate FLI to produce a constant scorch height. Due to different crown morphology of each species, crown scorch height will affect each species differently. The nature of prescribed fire eliminates the diversity of FLI typical from a wildfire freely spreading. In this case ABICON will experience greater crown damage compared to similarly sized PINJEF at diameters lower than 30 cm. This species-specific response suggests that practitioners may need to adapt firing techniques based on stand composition and species-specific traits (e.g., crown shape, morphology, or branch deposition) to achieve desired ecological objectives, as noted by Molina et al. (2022).

A critical insight from our work relates to the practical field implementation of prescribed burns. Unlike variables that are challenging to assess visually during operations (such as FLI or heat flux), burn bosses require readily identifiable field indicators that help achieve desired results while avoiding fire escapes or excessive tree mortality. Flame length, which correlates well with FLI (Byram, 1959), serves as a primary visual clue that burn bosses use to adjust FLI and prescribed fire performance. When flame lengths exceed desired thresholds, firing patterns are modified to reduce torching, tree mortality, and spotting potential.

Our analysis suggests that burn managers continually adjust flame length relative to crown base height across the burn unit. This adaptive approach indirectly produces the remarkably consistent crown scorch height effects we observed across diameter classes in our extensive dataset.

5. Conclusions

Our study demonstrates that prescribed fires in California forests are effectively reducing fuel loads and selectively modifying forest structure in the smallest diameter classes. The significant influence of human decision-making on burn outcomes, particularly through the selection of burning conditions and control of firing patterns, highlights the need to integrate human factors more explicitly into prescribed fire science and management.

The findings from the California Prescribed Fire Monitoring Program describe a situation where human factors are driving prescribed fire effects toward the conservative end of the possible range. Understanding these factors is crucial if we aim to expand the surface affected by prescribed fires. Under current operational parameters, prescribed fire may not fully achieve maximum ecological restoration objectives in mature stands. The observed effects are more likely to successfully shape forest development when applied to younger stands (DBH less than 30 cm), where the impacts we measured will influence future stand structure more substantially.

Crown scorch height emerges as a critical operational indicator for practitioners, providing a reliable visual reference for adjusting firing patterns to achieve desired ecological outcomes. The compensatory relationship between live and dead fuel moisture content reveals how practitioners navigate seasonal burning windows to maintain FLI within safe, controllable limits.

These findings support a more nuanced approach to prescribed fire planning that acknowledges both ecological objectives and human decision-making constraints. By better understanding these relationships, land managers can develop more effective prescribed fire strategies that balance safety considerations with ecosystem restoration goals, ultimately expanding the application of this essential management tool across California's fire-adapted landscapes.

CRediT authorship contribution statement

Rut Domènech: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marc Castellnou:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Victor Resco de Dios:** Writing – review & editing, Validation, Formal analysis. **David B. Sapsis:** Writing – review & editing, Validation, Conceptualization. **Joseph Restaino:** Writing – review & editing, Validation. **Hugh D. Safford:** Writing – original draft, Validation, Funding acquisition.

Funding sources

Funding was provided by the California Department of Forestry and Fire Protection [3540-8CA06198, June 2023].

Declaration of competing interest

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

Acknowledgements

We gratefully acknowledge the Safford lab graduate students and scientists (Ashley R. Grupenhoff, Tessa Putz, and John Williams) and the field crews who contributed to data collection from 2019 to 2024. We also thank Pau Guarque, Simon Schütze, Marta Miralles and Eric Rowell for their valuable comments and feedback on the manuscript. Àngel Cunill Camprubí assisted with LFMC and DFMC calculations. We sincerely thank the three reviewers who helped to improve this manuscript with their comments.

Codes and acronyms

CBH	Crown base height
DBH	Diameter at breast height
DFMC	Dead fuel moisture content
FLI	Fireline intensity
LFMC	Live fuel moisture content
SH	Scorch height
TH	Tree height

Species names

ABICON	*Abies concolor*
CALDEC	*Calocedrus decurrens*
PINCON	*Pinus contorta*
PINJEF	*Pinus jeffreyi*
PINLAM	*Pinus lambertiana*
PINPON	*Pinus ponderosa*
QUEWIS	*Quercus wislizenii*
SEQSEM	*Sequoia sempervirens*

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.127866.

Data availability

Data will be made available on request.

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