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Representing prescribed fire and mechanical thinning in a demographic vegetation model: mechanisms driving forest structure, fuel, and demographic rates in California mixed-conifer forests

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Abstract

Prescribed fire and mechanical thinning are common fuel management and forest restoration practices in fire-prone ecosystems, particularly where long-term fire suppression has led to significant fuel accumulation and altered stand structure. Existing field evidence shows varied outcomes depending on environmental and stand conditions, with long-term, landscape-scale management effects remaining poorly understood. The majority of large-scale models that project long-term effects lack mechanistic management processes and are rarely validated for the ecological processes driving outcomes. To address this, we implemented a new prescribed fire model and adapted a pre-existing wood harvest model to represent restoration thinning in the Functionally Assembled Terrestrial Ecosystem Simulator (FATES), a dynamic vegetation demography model. We developed a model validation framework emphasizing the key ecological mediators and expected feedback between management, vegetation, and fire. Running simulations with varying weather conditions under which prescribed fire can occur (burn window) and with the forest thinning model across three sites in California's mixed conifer forests, we found that FATES successfully captured the observed relative changes in stand structure, tree size distribution, fuel load, and demographic rates following forest health treatments. Additionally, model results aligned with general ecological expectations and reproduced the key differences between thinning and prescribed fire: logging immediately and significantly reduces stem density and basal area but not surface fuel load, while prescribed fire results in nonsignificant to moderate reduction in stem density and basal area but an immediate decrease in surface fuel load. Notably, simulations with a wide, inclusive burn window resulted in cooler fires and caused less change in stem density and basal area than those with a narrow, exclusive burn window, but only at the warmest and driest modeled study site. Our work advances the integration of management activities into Earth system models by introducing a mechanistic, interactive prescribed fire model, and a validation framework grounded in empirical data to assist model evaluations and applications. The model provides a promising tool for projecting the complex climate-vegetation-fire-human interactions in dry conifer forests of the Western U.S. and other fire-adapted ecosystems with similar management history.

1 Introduction

Fire is one of the key ecological processes that maintains biodiversity and ecosystem function for fire-adapted ecosystems. As a natural phenomenon, fire can reset the successional stage, create and maintain structural diversity, reduce future wildfire risk, and recycle nutrients through its effects on vegetation, soil, and belowground microbial community (Fernandes and Botelho, 2003; Pellegrini et al., 2020; Zhai et al., 2021). Recurrent low- to moderate-intensity fires help maintain the coexistence of species varying in growth form (e.g. woody vs herbaceous plants) and create heterogeneous forest and fuel mosaics at the

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landscape scale (Higgins et al., 2000; Schoennagel et al., 2008). In many regions of the world, including the Western U.S., human application of fire, including Indigenous burning practices and/or agropastoral land-use, played an important role in maintaining historical low- to moderate-severity fire regimes (Burrows and McCaw, 2013; Fernandes et al., 2013; Ryan et al., 2013). The removal of these processes via fire exclusion and suppression policies, in combination with hotter and drier climate, has been associated with increasingly damaging wildfire, which in part is due to accumulation of both surface fuels and understory vegetation during a long, relatively fire-free period (Hagmann et al., 2021; Kreider et al., 2024). To restore the resilience of these forests, the implementation of forest health treatments that mimic the ecological effects of fire is increasingly recognized as an important direction for forest management (Brodie et al., 2024; North et al., 2015; Schwilk et al., 2009; Stephens et al., 2009). Policies to accelerate prescribed fire and mechanical thinning as treatments have been developed for some dry conifer forests of the Western U.S. that were historically surface-fire dominant but are now crown fire-prone after a century of fire suppression. The state of California, for instance, has set a target to increase the application of "beneficial fire" (prescribed burning, cultural burning, and managed wildfire) and other fuel reduction activities to 2.5 million acres per year by 2045, up from approximately 1 million acres in 2023 (California Wildfire & Forest Resilience Task Force Dashboard, Administration of Governor Gavin Newsom 2024).

Increasing the pace and scale of prescribed burning and mechanical thinning to these recently unprecedented levels will require a regional approach to planning. However, allocating forest health treatments at this scale is challenging without higher fidelity models because forest and wildfire responses to treatments can vary dramatically depending on prescription, initial stand structure and fuel load, and post-treatment environmental conditions (Burke et al., 2021; Davis et al., 2024; Prichard et al., 2020). For instance, while prescribed fire and thinning reduced wildfire size and severity in some cases (Collins et al., 2023; Prichard et al., 2010; Safford et al., 2012), they also tended to have neutral effects or even intensified subsequent fires in other cases (Banerjee et al., 2020; Taylor et al., 2021). Climate is another factor that can influence management planning and outcomes. For instance, a warmer and drier climate is expected to limit the duration of the burn window (i.e., weather conditions needed to achieve a relatively low-intensity fire in a given fuel and vegetation context) and slow post-fire plant recovery (Nolan et al., 2021; Swain et al., 2023). In contrast, elevated atmospheric CO_2 concentration (eCO_2) can potentially increase fuel moisture content via more favorable plant-water relations, leading to better conditions for low- to moderate-intensity prescribed fire under dry conditions (Balaguer-Romano et al., 2023). Yet eCO_2 also stimulates growth which can increase landscape flammability (Allen et al., 2024; Manea et al., 2015). The net effect of changing climate and eCO_2 thus remains unknown.

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Models of forest health treatments have the potential to support planning for widespread forest management. Process-based models, including individual-based forest gap models (e.g., SORTIE, Pacala et al., 1993), forest landscape models (e.g., LANDIS, Mladenoff, 2004), hydro-ecological models focusing on the watershed scale (e.g., RHESSYs, Tague and Band, 2004), and dynamic global vegetation models (DGVMs e.g., LPJ-GUESS, Lindeskog et al., 2021) are powerful tools for projecting long-term ecosystem dynamics. Previous modeling experiments have investigated the effectiveness of alternative management scenarios in enhancing ecosystem resilience and mitigating wildfire risk at decadal or century scales (Ager et al., 2020; Bergkvist et al., 2025; Burke et al., 2021; Daum et al., 2024; Hanbury-Brown et al., 2025; Hurteau, 2017; Rabin et al., 2022). Due to more mechanistic representations of local and landscape processes in individual-based and landscape models, it is computationally expensive to run these models at continental or global scales. In contrast, while typically lacking spatially explicit landscape processes, DGVMs are coupled to global Earth system models (ESMs), making them ideal tools for projecting Earth system feedbacks. With ESMs, it is possible to explore the complicated interactions that are increasingly important for understanding the role of forest management in the carbon cycle and climate system (Cheng et al., 2024; Liang et al., 2025).

The representation of biomass harvesting (e.g., mechanical thinning) is fairly consistent across process-based models (e.g. LPJ-GUESS, FATES, and LANDIS); standing biomass is physically removed according to user-defined criteria, and fuel load is reduced primarily by targeting coarse woody fuels (Huang et al., 2020; Lindeskog et al., 2021; Syphard et al., 2011). The process of prescribed fire, however, can vary among models substantially. For instance, the earlier version of LANDIS-II and the ED model have used a biomass harvest model and post-event fuel manipulation to represent prescribed fire effects on standing biomass and fuel load, lacking mechanistic climate-fire-vegetation feedback (Flanagan et al., 2021; Syphard et al., 2011). Similarly, recent work using the Dynamic Temperate and Boreal Fire and Forest Ecosystem simulator (DYNAFFOREST) simulated diverse management scenarios given fuel load, land ownership, and treatment access, but did not represent climate effects on management implementation nor direct effects of management on vegetation (Daum et al., 2024). Recent implementation of the Social-Climate Related Pyrogenic Processes and their Landscape Effects (SCRPPLE) fire model into LANDIS-II improved prescribed fire representation by incorporating a burn window concept using fire weather index and wind speed (Scheller et al., 2019). LANDIS-SCRPPLE also computes prescribed fire-induced vegetation mortality, though it does so in a categorical way. The coupling of the SIMFIRE-BLAZE model into LPJ-GUESS enables simulation of prescribed fire with minimized tree biomass loss when weather- and fuel-dependent fireline intensity is within 3000 - 7000 kW m^{-1} (Rabin et al., 2022). While both LANDIS-SCRPPLE and LPJ-GUESS-SIMFIRE-BLAZE have a more mechanistic prescribed fire process by accounting for the interaction between vegetation, fire, and

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weather to some extent, a limitation of these models is that they assume that prescribed fire would have homogeneous effects on species with different fire tolerance strategies or that post-fire mortality only occurs for pre-specified fire intensity.

Prescribed fire and mechanical thinning can achieve similar management objectives (e.g., fuel reduction) but through different processes, and as a result, may have distinct ecosystem outcomes, including distinct interactions with climate. Capturing these nuances in models requires differentiated representation of these two processes, as well as an approach to model evaluation that ensures a range of outcomes is faithfully reproduced. Figure 1 provides an example evaluation framework, highlighting the different ecological processes through which mechanical thinning and prescribed burning influence two common forest management outcomes in the dry conifer forests of the western United States: a) reducing wildfire severity, and b) enhancing long-term carbon balance. Four well-established processes through which prescribed burning and mechanical thinning reduce wildfire severity include: 1) reducing surface fuels; 2) increasing canopy base height (height to the live crown); 3) decreasing stand-level bulk density of crown volume; and 4) retaining large, fire-resistant trees (Agee and Skinner, 2005; Figure 1a). The first three processes can prevent escalation of surface fire to crown fire by reducing fireline intensity and increasing the energy threshold for igniting and sustaining crown fire, and the last process aims to promote landscape fire resilience such that the ecosystem can resist and/or recover from fire damage. Recent meta-analyses indicate that prescribed burning consistently reduces surface fuel loads, however, the effect of mechanical thinning depends on whether the treatment removes thinning residues (e.g., via follow-up pile or prescribed burning) (Agee and Skinner, 2005; Davis et al., 2024; Fulé et al., 2012; Grupenhoff et al., 2025). Similarly, prescribed burning is generally expected to increase canopy base height by removing small trees, whereas mechanical thinning will affect canopy base height only if the small, usually unmerchantable, size classes are removed. In contrast, mechanical thinning consistently reduces canopy bulk density by removing trees in intermediate size classes, but prescribed burning alone does not consistently affect this component except in cases of relatively intense fires (Agee and Skinner, 2005; Davis et al., 2024; Grupenhoff et al., 2025). Finally, since thinning allows for the selection of individual trees to cut or retain, it is often used to increase the relative abundance of large, fire-resistant trees. Prescribed burning, on the other hand, is not known to predictably change forest composition when applied at a low intensity.

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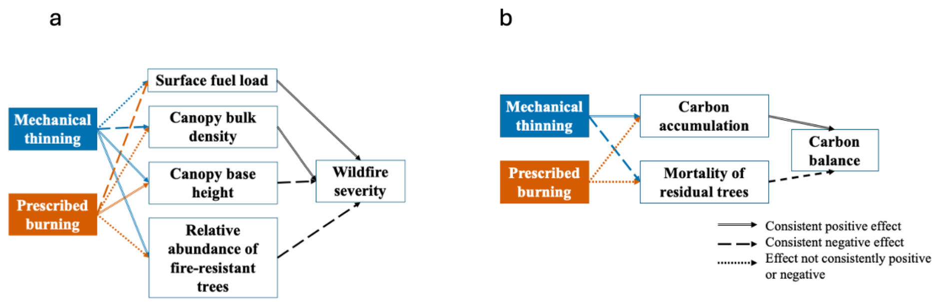

Figure 1. Framework for evaluating how process-based models represent mechanisms by which mechanical thinning and prescribed burning influence (a) wildfire severity and (b) carbon balance. Arrows indicate how the treatments affect processes and processes affect outcomes based on forest health treatment experiments (Agee and Skinner, 2005; Bernal et al., 2025; Davis et al., 2024; Grupenhoff et al., 2025; Stephens et al., 2012, Katz et al. *in revision*).

Similarly, the processes through which mechanical thinning and prescribed burning impact carbon balance, i.e., the difference between carbon accumulation and loss, can also differentiate treatment effects (Fig. 1b). Treatment can stimulate carbon accumulation by increasing tree growth and/or regeneration. A recent meta-analysis of growth responses to treatments in yellow pine and mixed conifer (YPMC) forests of the California Sierra Nevada suggests that thinning consistently increases growth, but prescribed burning does not have a consistent positive or negative effect (Katz et al. *in revision*). Treatment can also contribute to carbon balance via reduced mortality, including due to drought and wildfire. Mechanical thinning is associated with lower mortality rates during the post-treatment period, likely due to reduced competition for resources such as water (Bernal et al., 2023; Knapp et al., 2021; Steel et al., 2021), though drought can offset this response if treatment leads to structural overshoot (i.e., post-thinning growth that cannot be sustained during drought) (Goodwin et al., 2020). While some studies in western mixed-conifer forests have found higher drought-induced mortality following prescribed burning (Knapp et al., 2021; Steel et al., 2021), others have documented lower mortality in prescribed burned plots relative to the control (Van Mantgem et al., 2021). These differences may reflect the degree to which prescribed burning intensities were sufficient to significantly reduce competition. Faithfully representing these different mechanisms in process-based models and validating model results with field data are important to credibly simulate the no-analog combinations of future climate and forest management.

In this work, we aim to 1) introduce a new, mechanistic prescribed fire model for FATES, an ESM-coupled dynamic vegetation demographic model; 2) describe modifications to a pre-existing wood harvesting model to represent mechanical thinning as a fuel management approach; and 3) apply a new model benchmarking framework with the primary goal of determining if known key processes and state

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variables mediating the complex climate-vegetation-fire feedback in YPMC forests of Sierra Nevada are accurately captured by these schemes. Since the timing of prescribed fire, controlled by a burn window, can influence management outcomes through varying fuel and fire weather conditions, we also 4) explore how uncertainty in burn window parameters influences prescribed fire effects on vegetation and fuels.

2 Materials and Methods

2.1 The Functionally Assembled Terrestrial Ecosystem Simulator

FATES is a cohort-based dynamic vegetation demographic model that is embedded in the community land model (CLM5; Lawrence et al., 2019), which was used for this work, and the E3SM land model (ELM; Golaz et al., 2019), and thereby can be coupled to atmospheric models to simulate climate-vegetation-fire feedbacks. Canopy energy balance and soil hydrology are resolved by the land surface model. Species are represented as plant functional types (PFTs) in FATES, and defined by a comprehensive set of model parameters to reflect morphological and functional diversity (Buotte et al., 2021; Koven et al., 2020). Cohorts are the essential unit simulated, and are differentiated by PFT and size, co-occurring on patches that differ in disturbance history (Moorcroft et al., 2001). FATES resolves plant competition for light, water, space, and nutrients to track community succession at the patch level (Fisher et al., 2015; Knox et al., 2024), which can be reset by disturbances such as fire. To simulate wildfire, FATES uses the SPITFIRE approach (Thonicke et al., 2001), but also simulates fuel dynamics since last disturbance, enabling it to predict subsequent fuel conditions and fire risk (Shuman et al., 2024). These processes lay the foundation for using FATES to simulate how prescribed fire and thinning affect wildfire risk and forest resilience. Fire behavior and fire effects are largely determined by fuel load and fuel moisture content. Fuel load is the sum of leaf litter, aboveground fine woody debris (FWD, including 1-, 10-, and 100-hr fuels), and live grass when a grass PFT is included in a simulation. Fuel moisture content for both dead and grass fuels is a function of fire weather and fuel dimension. Patch-level fuel characteristics, including fuel moisture content, are then calculated as the fuel-load-weighted average across the five fuel size classes. Post-fire plant damage and mortality are predicted given fire intensity, heating duration, and PFT-specific fire resistance and resilience traits such as bark thickness and resprouting probability (Hanbury-Brown et al., 2025; Shuman et al., 2024).

2.2 Implementation of a prescribed fire model in FATES

We developed a new prescribed fire model to simulate controlled burning as a fuel reduction strategy in FATES (Fig. 2, referred to as FATES-RX hereafter). FATES-RX incorporates the burn window concept by checking weather conditions for temperature, relative humidity, and wind speed against a user-defined range for each of the three variables on a daily scale. A burn window presents when all variables are

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within the defined range. In the presence of a burn window, FATES-RX then checks fuel load and the pre-calculated fire intensity for each patch, and flags patches as suitable for conducting prescribed fire if both the fuel load and fire intensity are within a user-defined range. The reason for checking fuel load is to ensure that management resources are allocated to patches with sufficient fuel to burn but which are less likely to escalate fire into extreme wildfire incidents. The fire intensity check is used to achieve desired management outcomes such that a low- to moderate-intensity fire can remove litter and understory vegetation without significantly affecting large trees. This also enables the user to apply prescribed fire for various management scenarios, of which some might require more intense fires. Finally, FATES-RX checks if a minimum fraction of a grid cell, defined by the user, is suitable for conducting prescribed fire. This check is to prevent burning an extremely small portion of land, which is impractical for management planning. Once all conditions are met, prescribed fire is triggered if no wildfire is occurring on a patch. Total prescribed fire burned fraction across patches is a user-defined parameter in FATES-RX that can be set to reflect limits to institutional capacity to treat the landscape. The burned fraction of each patch where prescribed fire is allowed is constant across patches, i.e. prescribed fire generates larger absolute burned areas on larger patches, but proportionally equal across all patches that meet the above criteria on a given day. Prescribed fire behavior and fire effects on vegetation are predicted by SPITFIRE to account for the vegetation-fire interaction. FATES-RX thus 1) enables mechanisms of management fire to affect climate-vegetation-fire feedbacks in an ESM context; 2) accounts for a comprehensive set of factors that can influence the planning, occurrence, and effects of prescribed fire; and 3) allows user-defined parameters for a broad range of model applications.

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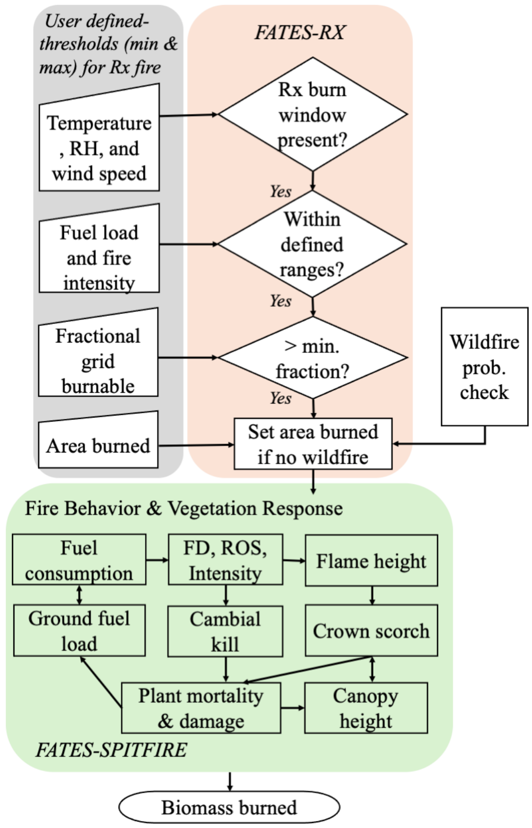

Figure 2. FATES prescribed fire model logic. Fire weather, fuel load, and fire intensity are user-defined model parameters controlling conditions under which prescribed fire occurs in FATES-RX. Area burned is a user input to reflect institutional burn capacity. Other prescribed fire behavior metrics such as fire intensity and fire effects are computed by SPITFIRE. RH: relative humidity; FD: fire duration; ROS: rate of spread.

2.3 Logging model and relevant model structure change

Logging in FATES operates at the patch level with user-defined frequency, intensity, and spatial extent (Huang et al., 2020). Logging is triggered at a specified time either as a single or recurrent event with the model searching for cohorts within the user-defined diameter range and applying user-defined mortality rates. Logging-induced mortality includes direct felling and collateral and infrastructural damage to reflect both direct and indirect mortality caused by logging activity. The target patch is then split into a disturbed and an intact patch given the defined logging spatial extent. The model then applies survivorship to trees on the disturbed patch, transports felled logs (1000-hour fuel) off site into a product pool, and transfers remaining biomass into size-defined fuel classes. We used the logging model to

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simulate mechanical thinning effects on stand structure and fuels. To better model the thinning practice, we modified the code to prioritize removal of understory trees by always starting thinning from the smallest tree size and then moving up the size class until a target stand basal area is reached. At each size class (as defined by diameter thresholds), we apply a user defined logging mortality rate. To ensure logging can help achieve the target stand basal area, we calculate the difference between the target and the initial stand basal area (delta basal area hereafter) before logging starts, and update the delta basal area after the partial cohort is removed during the logging event. Logging continues until the delta basal area is close to zero, allowing certain precision (0.01 m^2 ha^{-1} in this case).

2.4 Study sites and available observations

We validated modeled vegetation responses to mechanical thinning and prescribed burning using data from California's YPMC forests, an approximately 3 million hectare (ha) lower-montane ecosystem (Safford and Stevens, 2017). Prior to European contact, frequent fires, resulting from lightning and ignitions by Indigenous people (Anderson, 2005; Cuthrell et al., 2016; Klimaszewski-Patterson et al., 2024), shaped species distribution across these forests, resulting in open and patchy forest structures and the coexistence of diverse plant functional types (e.g. shade-tolerant, fire-susceptible firs alongside shade-intolerant, fire-resilient pines) (Knight et al., 2020). During this period, the absence of a continuous dense understory and low fuel load on the forest floor prevented the propagation of surface fire into the tree canopy, reducing crown fire probability and associated severe impacts. Fire suppression policy that started in the early 20th century led to a century-long, relatively fire-free period across the Western U.S. (Busenberg, 2004), after which dramatic changes in fuels, stand structure (e.g. increases in stem density), and community composition (e.g. transitions to the dominance of fire susceptible species) are documented at the regional scale (Hagmann et al., 2021).

We leveraged empirical data from three treatment experiments (hereafter, "sites") in YPMC forests: the Fire and Fire Surrogate Study located at Blodgett Forest Research Station ("Blodgett") (Stephens and Moghaddas 2005), the Variable Density Thinning Experiment located in the Stanislaus-Tuolumne Experimental Forest ("STEF") (Knapp et al., 2012), and the Teakettle Ecosystem Experiment ("Teakettle") (North et al., 2007) (Fig. 3). Conditions at these sites are representative of the geographically and climatically heterogeneous YPMC region. With elevations ranging from 1,380 to 2,050 m, each site experiences the warm, dry summers and cool, wet winters characteristic of a Mediterranean climate. Mean annual temperatures over the 1991-2020 period ranged from 9.2 °C at STEF to 13.4 °C at Blodgett, and mean annual precipitation ranged from approximately 1,050 mm at Teakettle to 1,360 mm at Blodgett (PRISM Climate Group, Oregon State University 2025). Soils are primarily derived from granite at Blodgett, from granodiorite at Teakettle, and from a mix of granite and volcanic

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parent materials at STEF (Soil Survey Staff 2022). The forest composition at all sites includes incense cedar (*Calocedrus decurrens* (Torr.) Florin), Ponderosa pine and/or Jeffrey pine (*Pinus ponderosa* Lawson & C. Lawson and *Pinus jeffreyi* Balf, respectively), white fir and/or red fir (*Abies concolor* (Gordon & Glend.) Lindl. ex Hildebr. and/or *Abies magnifica* A. Murray bis, respectively), sugar pine (*Pinus lambertiana* Douglas), and black oak (*Quercus kelloggii* Newberry). Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is also prevalent at Blodgett.

Each site implemented a full-factorial treatment experiment that included at least two thinning treatments (thinned and unthinned) and two prescribed burning treatments (burned and unburned). All sites had multiple replicates of each treatment type; we refer to these replicates as units. STEF and Teakettle each implemented three thinning treatments (unthinned, understory thin, and overstory thin at Teakettle; and unthinned, low variability thin, and high variability thin at STEF). For the model validation exercise, we only used observations from the unthinned and understory thin treatments at Teakettle, and we pooled observations from the low and high variability thin treatments at STEF. We did not include data from treatments that combined thinning and burning at any of the sites. Table 1 describes the prescriptions and timelines associated with each experiment; additional treatment design details are reported in Stephens and Moghaddas (2005) for Blodgett, Knapp et al. (2012, 2017) for STEF, and North et al. (2007) for Teakettle.

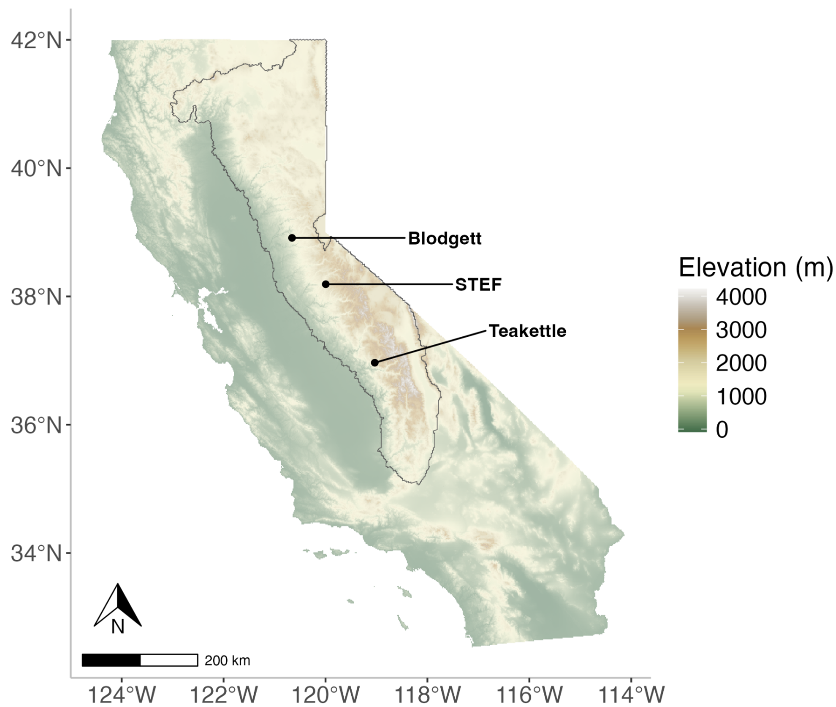

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Figure 3. Locations of the three validation sites, superimposed over elevation and a delineation of the Sierra Nevada ecoregion.

2.5 Simulation setup

We ran CLM-FATES with four PFTs, including pine, cedar, fir, and oak, to represent the dominant vegetation types in SNMC forests. All PFTs use an evergreen phenology and calibrated PFT-specific allometry, physiology, and stress tolerance parameters starting from Hanbury-Brown et al. (2025) and followed by comprehensive parameter optimization using observed plant traits and the trade-offs among them. PFTs are parameterized to capture relative differences in tolerance to drought, shade, and fire such that: pine and oak are more fire resistant than cedar and especially fir, with oak being a resprouter; fir and cedar are shade tolerant; oak and cedar can better tolerate drought than pine and especially fir. We further refined model parameters related to leaf biomass allometry and carbon starvation mortality to improve the persistence of understory trees in the model.

At each site, we conducted a control simulation without treatment, a thinning only simulation, and two simulations with prescribed fire treatments using different burn window settings. We initialized CLM-FATES using site-level pre-treatment observations and then ran 20 years of spin-up to reach fuel equilibrium. When treatment and control units had distinct pre-treatment size structure, treatment-specific inventory data were used for initialization (Blodgett, STEF); otherwise, inventory data generalized across all treatment units were used to characterize the average size structure, and all simulations at the site shared the same initial conditions (Teakettle). This approach preserved any significant differences in initial stand conditions between control and treatment units in the observations, allowing a more accurate assessment of relative treatment effects. We then restarted CLM-FATES for the four model experiments from the spun-up conditions.

All model experiments followed site-specific treatment prescriptions, with some details differing from site practice due to model structure constraints (Table 1). For instance, CLM-FATES currently does not preferentially remove certain PFTs over others during thinning, which is part of the thinning practice at the validation sites. In addition, the timing of a prescribed fire cannot be specified with FATES-RX to match the observation. However, modeled prescribed fire, except the first entry, always happens in the same year as the observations with a similar fire return interval. To constrain prescribed fire at the observed frequency, we implemented a fire return interval control on prescribed fire occurrence in FATES-RX. When the total burned area of one or several consecutive prescribed fires is greater than 95% of the site area, the next prescribed fire is paused until a defined number of years (Table 1) has passed. For thinning, because the site prescriptions did not consistently define a post-thinning target basal area

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and/or the percentage of stems to target for removal in each size class, we derived these values using pre- and post-treatment inventory data from each site.

Table 1. Study design and treatment details for the three study sites with modeled treatment for comparison. Rx FRI: prescribed fire return interval; TBA: target basal area; DBH: diameter at breast height.

Site (alias)	Site treatment prescriptions	Modeled treatment and relevant settings
Blodgett Fire and Fire Surrogate Study (Blodgett)	**Burn**: ● Broadcast burns in the falls of 2002, 2009, and 2017 **Thin**: ● Thin from below, followed by mastication of 90% of trees <25cm DBH in 2001; mastication in 2017; thin from below in 2019 ● TBA of 28-34 m^2 ha^{-1} ● Retain an even species mix ● Remove only trunks larger than 25cm DBH from site Post-treatment measurement years: 2003, 2009, 2016, 2020 Source: Bernal et al. 2025	**Burn**: ● Rx FRI is set at 8 years with fires occurring in 2001, 2009, and 2017 **Thin:** ● Thinned in 2001, 2017, and 2019 ● TBA of 40 m^2 ha^{-1} ● No PFT preference ● Max. thinning rate for size groups: ○ Below 25cm DBH: up to 70% of stems ○ 25-50 cm DBH: up to 60% of stems ○ 50-75 cm DBH: up to 10% of stems ● Remove 1000-hour fuels (logs) from site Model years: 2001-2020 Climate forcing data: 2001-2020
Stanislaus-Tuolumne Experimental Forest Variable Density Thinning Experiment (STEF)	**Burn:** ● Broadcast burn in fall of 2013 **Thin**: ● Thin from below in 2011 ● TBA of 45.9 m^2 ha^{-1} (range: 34.4-57.4 m^2 ha^{-1}) ● Preferentially remove fir and cedar over pine; no oak removal ● Remove all residues from the site Post-treatment measurement years: 2012, 2014, 2016, 2018 Source: Knapp et al. 2017; Knapp 2012	**Burn:** ● One burn in 2011. **Thin:** ● Thinned in 2011 ● TBA of 40 m^2 ha^{-1} ● No PFT preference ● Max. thinning rate for size groups: ○ Below 25cm DBH: up to 90% of stems ○ 25-40 cm: up to 75% of stems ○ 40-60 cm: up to 50% of stems ○ 60-80cm: up to 15% of stems ● Remove 1000-hour fuels (logs) from site Model years: 2011-2020 Climate forcing data: 2011-2020
Teakettle Ecosystem Experiment (Teakettle)	**Burn:** ● Broadcast burn in falls of 2001 and 2017 **Thin:** ● Thin from below in 2001 ● Remove trees between 25-76 cm DBH while retaining 40% canopy cover ● Remove only trunks from the site Post-treatment measurement years: 2002, 2004, 2011, 2016, 2017, 2018 (not all units were measured in all years) Source: North et al. 2007; Goodwin et al. 2020	**Burn:** ● Rx FRI is set at 16 years with fires occurring in 2001 and 2017 **Thin:** ● Thinned in 2002 ● TBA of 40 m^2 ha^{-1} ● No PFT preference. ● Max. thinning rate for size groups: ○ Below 25cm DBH: up to 35% of stems ○ 25-50 cm: up to 80% of stems ○ 50-75 cm: up to 90% of stems ○ 75-100cm: up to 20% of stems ● Remove 1000-hour fuels (logs) from site. Model years: 2001-2020 Climate forcing data: 2001-2020

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To parameterize the burn window, we conducted a parameter perturbation experiment using a range of weather conditions for historical management fires conducted in forested regions across the Western U.S. from Swain et al. (2023). Two sets of parameters were then selected to represent: 1) an "inclusive burn window" with more than 25% of each month, from April to November, when weather conditions favor management fire; and 2) an "exclusive burn window" with days suitable for conducting management fire mainly happening in the spring and fall (Supplement Figure S1). Simulated prescribed fire intensity is within 50 - 1200 kW m^{-1} with most fires under 600 kW m^{-1}, a typical fireline intensity observed for management fires in Sierra mixed conifer forest (Keifer et al., 2006). Fuel load was excluded from constraining prescribed fire occurrence to best reconstruct the field experiment conditions at each site.

The spin-up simulations were conducted with CO_2 concentration fixed at 380 ppm, using 1980-2000 ERA5 reanalysis data that is dynamically downscaled to 9km for California (Rahimi et al., 2022). The same forcing data source for 2001-2020 and a constant CO_2 concentration of 400 ppm were used to drive the four treatment simulations at each site. Simulation time, years of forcing data used, and timing of treatments were set to match the observational period for each site (Table 1). Wildfire was turned off for all simulations given none of the sites had wildfire during the observational period. Data from all model years of the treatment simulations were used for analysis.

2.6 Benchmark data and corresponding model metric development

To validate the ability of CLM-FATES to faithfully reproduce YPMC forest responses to treatment, we used the benchmarking framework outlined in Fig. 1. For each process, we identified one or more benchmarking metrics that could readily be synthesized both from modeled outputs and from field observations at the three experimental forests (Table 2). We compared observations and modeled outputs in two ways: first, we compared absolute values of the metrics in the control (Supplement figures S2-S6). Second, we compared differences between metrics in the treated units (i.e., mechanical thinning or prescribed burning) and the control. Calculation details for each benchmark (e.g., surface fuels, stand structure and PFT composition, and demographic rates) using observations and model outputs are provided in the Supplement.

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Table 2. Benchmarks for evaluating the ability of FATES to capture key ecological processes through which forest health treatments influence management outcomes.

Management outcome	Ecological Process	FATES benchmark metric(s)
Reduce wildfire severity	Reduce surface fuel load	Litter Fine woody debris (1-, 10-, and 100-hour fuel load)
	Increase canopy base height	Tree size distribution
	Reduce canopy bulk density	Stem density Basal area Tree size distribution
	Increase relative abundance of fire-resistant individuals	Species proportion of basal area
Increase carbon balance	Increase carbon accumulation	Growth rate by plant functional type and size class
	Reduce mortality of residual trees	Mortality rate

3 Results

Using inventory data initialization, followed by 20 years of model integration to allow the fuel load to spin up, CLM-FATES accurately represents the observed stand basal area, stem density, and size distribution for control units across all sites, capturing a dense forest structure dominated by trees smaller than 50 cm in diameter (Supplement Figures S2 & S3). Both modeled and observed PFT composition characterize a fir-dominant or co-dominant forest stand that is typical in fire-suppressed, dense mixed conifer forests (Levine et al., 2016; Parsons and DeBenedetti, 1979). The relative fir abundance also increases as the temperature decreases and precipitation increases, however, pine is underestimated while fir is overpredicted in the model (Supplement Figure S4). Modeled growth rates for pine, cedar, and fir matched the observed growth rates in control units for small trees (Supplement Figure S5). However, while both simulations and observations tend to show a unimodal distribution of growth rate across tree size, a greater size dependence of growth rate is observed in the model resulting in underestimates of growth rates for larger trees. Finally, CLM-FATES tends to overestimate FWD but underestimate leaf litter across sites (Supplement Figure S6).

The prescribed fire-induced relative reduction in stand basal area (~ -6–23%) and stem density (~ -5–38%) were best captured at Blodgett, with the other two sites showing either smaller or greater mean relative change in stand structure than the observations (Fig. 4). FATES-RX with an inclusive burn window (Model-BurnCool) resulted in lower intensity fires, leading to about 25% less relative stem density change as compared to the simulations using an exclusive burn window (Model-BurnHot, Fig. 4a

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& 4b). This burn-window effect on the relative structure change is greatest at Blodgett, with the other two sites showing no significant difference.

Over the full timeframe associated with each experiment, thinning always resulted in relative reductions in observed basal area and stem density. This thinning effect on basal area and stem density was generally well captured qualitatively by the model, but produced a greater reduction compared to observations at Blodgett (~ 36% and ~ 62% modeled relative reduction in basal area and stem density respectively vs ~ 24% and ~ 53% observed, Fig. 4a & 4b). At STEF, the modeled relative reduction in basal area (~38%) was the same as the observations, but the modeled relative reduction in stem density (~58%) was smaller than the observed 72% reduction. At Teakettle, simulations predicted a relative increase in stem density, which disagrees with site observations. Both the model and observations generally showed greater relative reductions in stand structure after thinning than after prescribed fire.

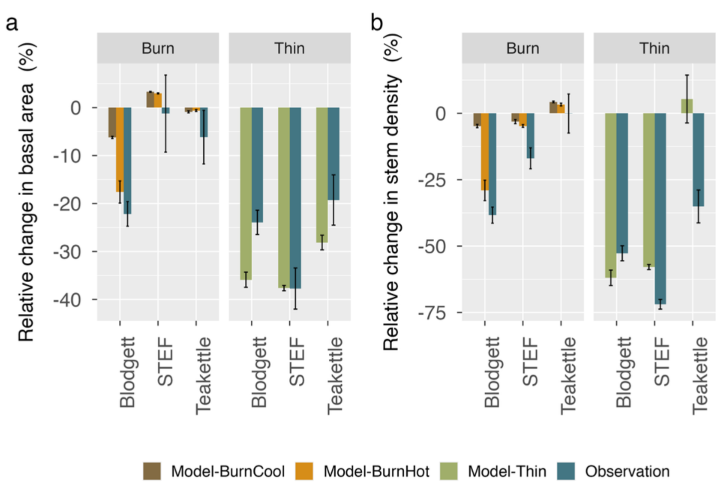

Figure 4. Modeled and observed change relative to the control (over the same time period) in stand basal area (a) and stem density (b) due to prescribed fire and thinning. Model-BurnCool represents the prescribed fire simulation using an inclusive burn window while Model-BurnHot refers to the prescribed fire simulation using an exclusive burn window. Model-Thin is CLM-FATES simulated thinning treatment.

Observed prescribed fire effects on stem density varied by size class and site: while prescribed fire reduced stem density of trees with diameter ≤ 50cm across all sites (Fig. 5), its effect on larger trees relative to the control was either positive (STEF and Teakettle) or negative (Blodgett). Note that observed relative change in size structure is partially due to the difference in initial stand structure between

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treatment and control. Modeled relative change in size structure due to prescribed fire generally followed the observed trend, with the burn window effect being more pronounced for trees with DBH ≤ 50cm.

In the observations, thinning resulted in a 10%–100% reduction, relative to control plots, in stem density of any given size class for trees with DBH ≤ 60cm across sites. While thinning led to relative reductions in larger trees (DBH > 60cm) at Teakettle, its relative effect on these larger trees was positive at Blodgett and STEF (Fig. 5). Again, these differences could be due in part to initial structure differences between treatment and control units. CLM-FATES captured the relative thinning effects on tree size structure for trees with DBH ≤ 50cm, in terms of both effect direction and size. For trees with DBH within 50-90cm, we saw large data-model deviations, especially at STEF, where the model showed > 50% relative reduction to meet the treatment prescription while observations indicated an increase in stem density relative to the control, presumably due to differences in initial stand structure (Fig. 5).

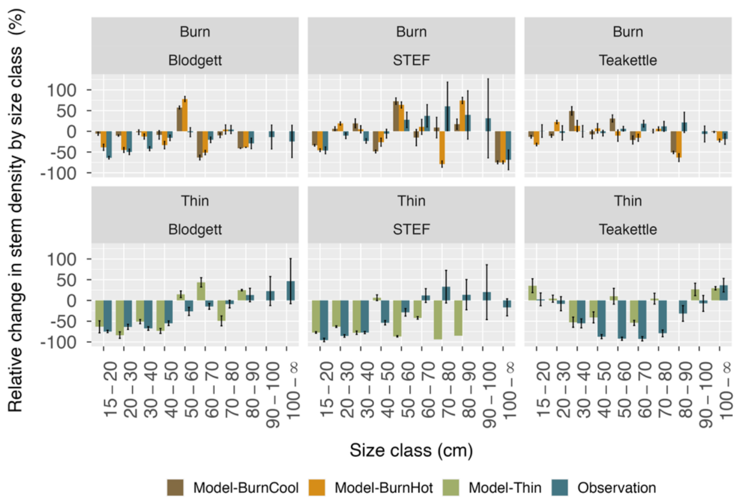

Figure 5. Modeled and observed change, relative to control, in size structure due to prescribed fire and thinning at three study sites. Model-BurnCool represents the prescribed fire simulation using an inclusive burn window while Model-BurnHot refers to the prescribed fire simulation using an exclusive burn window. Model-Thin are CLM-FATES simulated thinning treatment.

Following prescribed fire, the modeled percent basal area of pine tended to increase except at STEF; the increase in pine relative abundance is greatest following the intense fire (Model-BurnHot) at Blodgett, capturing the observed trend (Fig. 6). Similarly, thinning tended to increase the pine percent basal area in both the model and observations, except for at STEF where the model indicated ~30% decrease while observations showed up to 60% increase in pine percent basal area, with large variation across sampling units. The percent basal area of fir tended to increase following fire at Blodgett and following fire or

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thinning at STEF in both model and observation, in contrast with the expectation that fire-intolerant fir would be most negatively affected by prescribed fire. Lastly, the percent cedar basal area tended to decrease at Blodgett and STEF, but increase at Teakettle, after treatments in both the model and observations. We do not show change in oak percent basal area as it is a minor component of the stand that tends to vary widely in its relative abundance after treatments. A figure for the change in PFT composition including oak is provided in the Supplement (Figure S7).

Figure 6. Modeled and observed change relative to the control in percent basal area by PFT following prescribed fire and thinning at three study sites. Model-BurnCool represents the prescribed fire simulation using an inclusive burn window while Model-BurnHot refers to the prescribed fire simulation using an exclusive burn window. Model-Thin are CLM-FATES simulated thinning treatment.

Both model and observations showed reductions in FWD relative to the control across sites after prescribed fire and relative increases in FWD after thinning (Fig. 7a). However, site observations indicated > 50% reduction relative to control in FWD after fire at Blodgett, while modeled relative reduction was about 25%. In contrast, the thinning-induced relative increase in FWD fuels at Teakettle and Blodgett is much larger in the model (~ 200% and ~ 100% respectively) than the observations (~75% and ~ 30% respectively). Modeled leaf fuels tend to decrease significantly (~60%–75%) following prescribed fire but increase (~12%–25%) after thinning except at STEF, where we saw ~ 12% modeled decrease in leaf fuels after thinning. These treatment effects on leaf litter were also reflected in the observations at Blodgett, where prescribed fire led to ~60% reduction while thinning resulted in ~ 46% increase in leaf litter. Finally, there was no burn window effect on relative fuel change.

Detailed fuel component data broken down by treatment were not readily available for STEF; however, reported experimental results from this site provide qualitative benchmarks for modeled results (Knapp et

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al. 2017). Observations from STEF indicated that burned units (including both thinned + burned and burned only units) had significantly less FWD and leaf litter than unburned units; a qualitatively similar result was produced in the simulations. Observations from thinned units at STEF (averaged across burned and unburned units) indicated significantly less litter in the thinning treatments than in the unthinned control, with mean percent decreases estimated at approximately 9% and 25%, depending on the spatial arrangement of the thinning treatment. A qualitatively similar result was modeled for leaf litter following thinning at STEF. For FWD, no significant differences were observed between the thinned and unthinned units, except for 100-hr fuels, which increased by an average of 67–82%, depending on the thinning treatment. Simulated results showed a slightly greater increase (~100%) in total FWD after thinning.

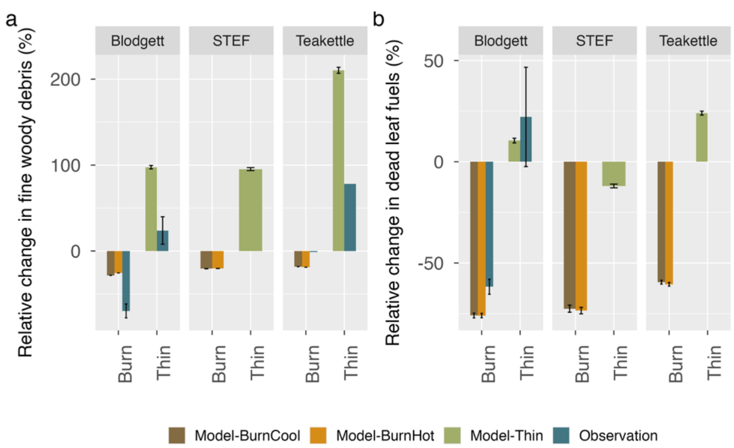

Figure 7. Modeled and observed change in fuel load relative to the control for fine woody debris (a) and leaf litter (b) at three study sites after prescribed fire and thinning. Observations are shown where available.

Simulated relative growth rate of 30-40 cm DBH trees, calculated as post-treatment growth rate divided by the control growth rate, captured site observations with both demonstrating a neutral or slightly positive effect of prescribed fire on the growth of cedar and fir (Fig. 8). Prescribed fire effect on yellow pine growth varied among sites: both model and observation showed stimulated pine growth after prescribed fire at Blodgett and Teakettle but reduced growth at STEF. In contrast, thinning tends to promote growth rate (1.5–3.5 times faster than in the control) across sites in both model and data. However, the modeled relative growth response of pine to treatments is about 3–10 times the observed response at Blodgett and Teakettle for this size range. No significant burn window effect on growth was observed in the model.

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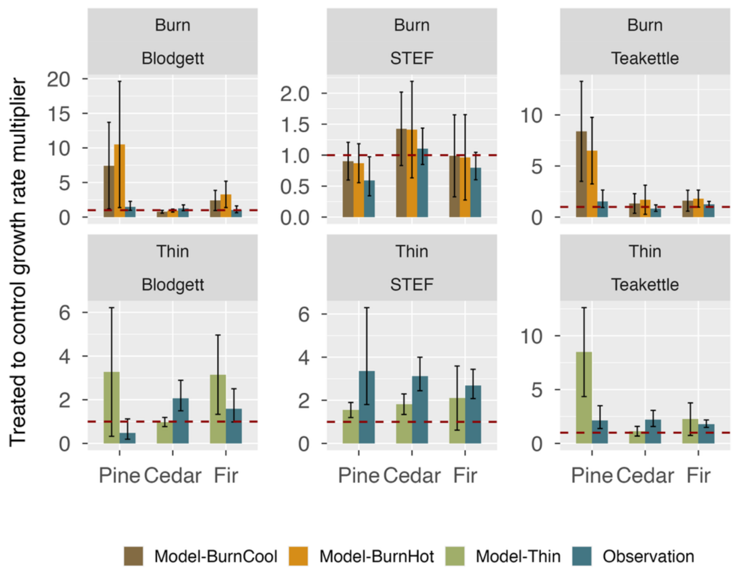

Figure 8. Modeled and observed post-treatment growth rate relative to control for pine, cedar, and fir for the 30-40 cm size class (~the median tree size) at three study sites. Error bars indicate the 95% credible intervals. The red dashed line indicates a relative growth rate of 1. A relative growth rate < 1 indicates that trees in the treatment grow slower than trees in the control; >1 indicates stimulated growth following treatment. Pine observations include ponderosa pine and Jeffrey pine but not sugar pine.

There were larger model-data discrepancies in cumulative mortality rate (calculated as the total multi-year mortality over the study timeframe, including mortality due to treatment) for small (DBH ≤ 60cm) and large (DBH > 60cm) trees (Fig. 9). In general, simulated cumulative mortality rates were lower than observations, except in the control for trees with DBH greater than 60 cm at Blodgett (~ 15% in the model) and in the prescribed fire with exclusive burn window case for both size groups at Blodgett (~105% and 35% for trees with DBH ≤ 60cm and DBH > 60 cm in the model, respectively). Simulated mortality in the mechanical thinning case (generally < 10%) was lower than observations (5–75%) across three sites for both size groups. Only Blodgett had significant burn window effects on mortality, with 16 and 2 times higher small and large tree mortality in the exclusive relative to the inclusive burn window simulations.

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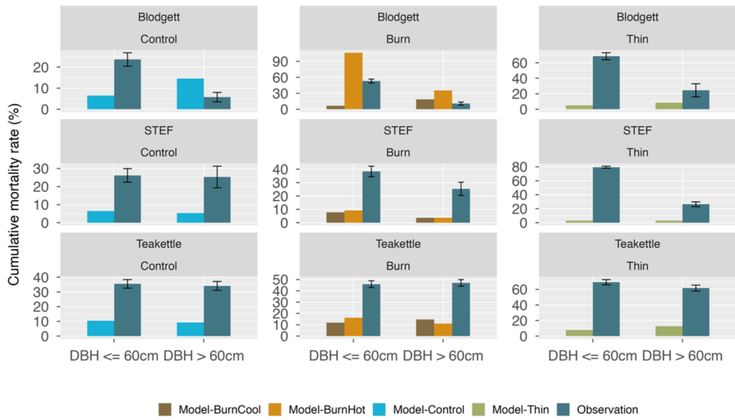

Figure 9. Modeled and observed cumulative mortality rate over the study periods (Blodgett: 2001-2020; STEF: 2012-2018; Teakettle: 2000-2018) for trees with DBH <=60 cm and > 60 cm by treatment at each site. Mortality rates include mortality due to the treatments for both model and observations.

4 Discussion

4.1 FATES-RX and forest thinning

We implemented a new prescribed fire model in CLM-FATES and adapted a pre-existing harvest model to better represent forest health treatment effects on properties that affect wildfire hazard and carbon balance across three sites in California Sierra Nevada mixed conifer forests. FATES-RX and the modifications to the harvest scheme enable these specific types of forest management to be implemented within at least three Earth system models (CESM, E3SM and NorESM) that are developing FATES as a vegetation demographic model option. Different from previous prescribed fire models, FATES-RX accounts for effects of both climate and vegetation dynamics on management fire planning and occurrence, and the feedback of management fire on vegetation demography, enabling future studies to explore complex climate-vegetation-fire-management interactions.

4.2 Benchmarking of the control conditions

Through application of an extensive new benchmarking framework under control and treatment conditions, we determined that the prescribed fire and thinning algorithms are largely having intended effects but highlight areas where lingering biases or mismatches may affect predictions. Remaining biases observed in control simulations could affect predictions of forest composition, forest carbon accumulation and fire behavior. Simulations under control conditions largely captured present forest structure and composition, but underestimated pine relative abundance and overestimated fir, likely due to the model emphasis on light competition and current model parameters not fully capturing relative PFT differences

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in shade tolerance. FATES also captured observed growth rates and their size dependence, but underestimates in large-tree growth rates in the present parameterization could contribute to underestimates of large tree carbon accumulation rate post-treatment even when relative change is simulated properly. Further parameter tuning that targets these biases may be sufficient to resolve them.

Finally, overestimation of FWD and underestimation of leaf litter across sites could potentially lead the model to project fire regimes under a hotter and drier climate that are unrealistic. For instance, less leaf litter would lead to a slower simulated rate of spread and smaller burned area because fine fuels drive the ignition and spread of fires; excess FWD, however, would cause longer fire duration and produce more energy, leading to more severe fire impacts (Alexander, 1982; Sullivan et al., 2018). Fuel load in the model is a result of both litter input and decomposition, which are determined by dynamic vegetation productivity, biomass allocation and turnover, mortality, and climate- and quality-driven decay rates (Gao et al., 2025). While we used optimized model parameters from previous work, there is limited data on woody litter decomposition rate and the turnover rate of plant structures including branches and leaves (Hanbury-Brown et al. 2025), which determine 100-hour fuel and leaf litter accumulation. Empirical work is needed for a better understanding of fuel turn over, especially for woody fuels, in these systems in order to better constrain predicted fuel dynamics.

4.3 Benchmarking of processes expected to reduce fire severity

Our benchmarking framework for the prescribed fire and thinning schemes (Fig 1, Table 2) first targets processes and variables that are expected to reduce wildfire severity (i.e., reduce surface fuel load, increase canopy base height, reduce canopy bulk density, increase relative abundance of fire-resistant individuals). As an indicator of change in canopy bulk density, modeled relative changes in stand structure resulting from forest health treatments qualitatively capture the patterns shown by observations, with modest reductions following prescribed fire and more dramatic structural changes after thinning, supporting the general expectation (Fig. 4). Post-fire relative reductions in basal area and stem density are much greater at Blodgett especially in the case with an exclusive burn window, while modeled fire effects at STEF and Teakettle tend to be neutral or less negative with < 5% relative change in stand structure, qualitatively reproducing site differences (Fig. 4). However, observations show a greater relative reduction (> 10%) in basal area and stem density at STEF and Teakettle compared to model results. While there are various factors influencing management fire outcomes (Agee and Skinner, 2005; Prichard et al., 2020; Schmidt et al., 2008), higher temperatures in the Blodgett simulations may have accelerated fuel drying to intensify prescribed fire under fire-prone weather conditions, potentially leading to higher post-fire mortality. This is supported by the significant burn window effect at Blodgett: when prescribed fires mainly happened during early-mid summer (e.g., June), there are greater reductions in basal area

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than when prescribed fires occur in late spring (e.g., May). However, the observed differences across sites could also be partially due to initial stand conditions that differ between control and treatment; observed structural changes between pre- and post-treatment surveys are not significantly different and even show an increase in basal area after prescribed fire at Blodgett (Supplement Figure S8). Therefore, the model overestimates prescribed fire induced mortality at Blodgett, especially in simulations with the exclusive burn window. Further, this model-data mismatch can be due to a hotter and drier model forcing compared to observed site meteorology at Blodgett and/or mismatched timing of fire between observations and model simulations, thus different weather conditions under which prescribed fire occurred.

Simulated relative reductions in basal area and stem density as a result of thinning are larger than post-fire relative change by a factor of 2-10, which mirrors the observed pattern. The main model-data disagreement is that stem density increased by about 10% after thinning at Teakettle due to the increased fir density in the model (Supplement Figure S9). This model result could be due to interactions of various processes: being the coolest site, Teakettle favors establishment of fir over pine and cedar given PFT differences in cold tolerance; Teakettle is also the site with the highest percent fir to start with, and thinning releases the growth of understory fir via reduced light and water competition contributing to increases in fir stem density (Wayman and North, 2007).

Reduced basal area and stem density in treated units relative to the control are mainly driven by the removal of small- and medium-size trees in both simulations and observations (Fig.5 and Appendix Figure S10). In addition to reducing canopy bulk density, this change in size structure can increase canopy base height to mitigate wildfire risk since small trees behave as ladder fuels to promote crown fire (Agee and Skinner 2005). As thinning can result in greater reductions in stem density, it is usually believed that thinning outperforms prescribed fire, especially low intensity fires, in terms of reducing extreme wildfire incidents (Stephens et al., 2009). However, if thinning has removed a large portion of tree stems such that the stand basal area is below a certain threshold, wildfire intensity can also increase due to higher wind speed in an open vegetation (Banerjee et al., 2020; Ma et al., 2010). While not tested here, FATES can potentially capture this dynamic because effective wind speed, which is used to calculate fire behavior, is a function of the modeled vegetation cover (Thonicke et al., 2001, Shuman et al., 2024).

Management that increases fire resistant functional types is also expected to reduce wildfire severity. FATES is able to reproduce observations showing an increase in relative pine abundance following prescribed fire and thinning, suggesting that simulated management can potentially enhance stand resilience. As the most fire-resistant species, simulated post-fire mortality is lower in pine compared to other species, especially fir (Supplement Figure S11), leading to a relative increase in pine abundance.

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While prescriptions that retain pine species (e.g., at STEF, Knapp et al. 2017) intentionally increase relative pine abundance after thinning, the cause of a similar model result is different. For these experiments, we did not apply selective harvest across species. However, pine has the most significant positive growth response to thinning and prescribed burning in the model, especially at Blodgett and Teakettle; and modeled thinning happens largely in small trees, which fir dominates. It is thus possible that the two underlying processes collectively lead to the increase in relative pine abundance in the model.

Finally, surface fuel loads are critical to wildfire behavior and effects. FATES successfully captures the observed decrease in surface fuels after prescribed fire and the observed increase after thinning, but the magnitude of these changes does not always align with empirical data due to complex processes not captured by the model. It is worth noting that prescribed fire can effectively remove surface fuels, whereas the effects of thinning on surface fuel load vary depending on the specific practice used (Agee and Skinner 2005). Both litter and FWD are reduced compared to the control following prescribed fire, with the modeled reductions being less than observations, especially for FWD. These responses are relatively insensitive to the choice of prescribed burn window representation (Fig. 7). The model-data discrepancy may be due in part to the fact that FATES does not represent delayed mortality or standing dead biomass. With instantaneous litter input from fire-induced mortality, the simulated reduction in surface load following prescribed fire is expected to be smaller than observations, especially given that the fuel load observations for the three validation sites were taken only one year post burning, before the onset of delayed mortality. Additionally, in the simulations, only felled logs (1000-hour fuel) were removed during thinning, with other biomass residuals being left. This representation was consistent with thinning prescriptions at Blodgett and Teakettle, both of which showed an increase in surface fuel load following thinning in both the model and site observations (Fig. 7). The model overestimated post-thinning fuel load at STEF, where most residuals were chipped and removed from the site (Knapp et al. 2017). Since thinning can potentially intensify subsequent wildfires if not followed by slash removal, the ability of process-based models to faithfully represent post-thinning fuel conditions and subsequent wildfire depends on the continued evolution of these models to capture the details of these practices. Empirical work suggests that combining thinning with prescribed fire is the most effective fuel management approach (Davis et al., 2024; Prichard et al., 2010; Shive et al., 2024). While we did not model the combination of treatments, our validation of the ability of CLM-FATES to separately represent the effects of thinning and prescribed burning lends confidence that this combined treatment can be introduced in future simulations.

4.4 Benchmarking of processes expected to increase carbon balance

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While not always a primary objective of forest treatments, our benchmarking framework also includes processes expected to increase forest carbon balance (i.e., increase carbon accumulation and reduce mortality of residual trees) following treatment. As expected, both model results and site observations suggest that thinning stimulated the size-dependent growth rate of dominant PFTs by a factor of 1.5-17 relative to the control; prescribed fire effects on growth tended to be neutral with the exception of a significant positive growth response in pine observed at Blodgett and Teakettle, especially in the model (Fig. 8). Site and PFT differences in treatment effects on growth are likely due to the diverse legacy effects of prescribed fire. Decreased stem density as a result of post-fire mortality reduces light and water competition, favoring growth of surviving trees. However, trees that survived prescribed fire can also experience reduced growth due to fire-induced damage such as crown loss or dysfunctional xylem (Bär et al., 2018; Stephens and Finney, 2002). While CLM-FATES currently does not represent fire impacts on plant hydraulic traits, trees can lose photosynthetic tissues after fire in the model, affecting post-fire growth (Shuman et al., 2024). The net effect of prescribed fire on growth thus depends on the post-disturbance environmental conditions and PFT-level fire resistance traits. As the most fire resistant and shade intolerant PFT, pine may benefit more from prescribed fire than the other PFTs, leading to an overall positive growth response in the model. Such a positive fire effect on pine growth is not uniformly observed across the study sites (Fig. 8) perhaps due in part to stresses on pine during the observational period that were not fully simulated, such as a strong drought and insect outbreaks (Fettig et al., 2019).

Modeled cumulative mortality tends to be lower than observations, except for prescribed fire simulations at Blodgett (Fig. 9). The underpredicted mortality in the model could be due to the absence of other disturbance processes such as bark beetle attacks that preferentially affected pines during the field experiments. Additionally, current model parameters likely underestimated drought-induced mortality in the model, which contributed to the widespread tree mortality across California mixed conifer forests during the 2012-2016 megadrought (Fettig et al., 2019; Kane et al., 2017; Ma et al., 2023). Further model validation for vegetation responses to drought is required for future work that aims to examine the long-term vegetation dynamics under changing climate. It is also critical to incorporate existing insect outbreak models into DGVMs to account for vegetation mortality caused by biotic stressors (Kautz et al., 2018; Sato et al., 2023), as well the complex interactions between drought, insect, and wildfire (Kane et al., 2017).

In this study, we did not directly test how different treatments influence subsequent wildfire severity or long-term carbon balance. However, given that FATES can largely capture the demographic, stand structure, and fuel dynamic responses to different management strategies, application of the model to the broader Sierra mixed conifer forest region and in similar fire-prone ecosystems is the clear next step. It is

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worth noting that while our proposed model validation framework highlights several key processes and mediators affecting management outcomes, other processes that are not included can be important as well. For instance, the spatial placement of treatment appears to be as or more important than treatment intensity and frequency, due to the resulting spatial heterogeneity in fuel distribution that suppresses fire spread (Ott et al., 2023; Prichard et al., 2010, 2020; Tubbesing et al., 2019). This particular management outcome, however, cannot be explicitly represented by FATES and other spatially implicit models, in which fires do not spread across the landscape. In addition, the absence of a crown fire model in FATES and most other process-based models impedes accurate projections of extreme wildfire behavior, which is the primary focus of fuel management. We can resolve the latter by implementing a crown fire model (Scott and Reinhardt, 2001). However, due to computational constraints, it is challenging to explicitly simulate the spatial interactions while also representing the complex ecosystem and biogeochemical processes in DGVMs (Argles et al., 2022). That said, the sub-grid patch structure in FATES may allow future creative implicit representations of spatial processes to provide reasonable approximations at the grid-cell scale (McCabe and Dietze, 2019).

4.5 Model sensitivity to burn window parameters

Modeled burn window effects are only significant for stand structure, percent pine composition, and mortality at Blodgett, where differences in post-fire mortality of small trees emerged (Fig. 5). The main difference between the inclusive and exclusive burn window is the significantly greater availability of days suitable for conducting prescribed fire in late spring and throughout summer in the former (Supplement Figure S1). This difference in burn window availability led to earlier fire occurrence (May vs June) in simulations and less small tree density reduction using the inclusive burn window. Among the three sites, model forcing data for Blodgett was hotter and drier in late spring and summer than at other sites (Supplement Figure S12). Therefore, simulated prescribed fires are more intense and result in higher mortality overall at Blodgett compared to other sites, particularly with an exclusive burn window (Fig. 9). The subtle structural changes following prescribed fires at STEF and Teakettle in the model indicate that applying a uniform burn window is likely not effective in achieving the goal of substantially altering canopy fuel structure at regional scale when varying weather conditions are expected. It is worth noting that the occurrence of prescribed fire in the model not only depends on the presence of a burn window but also on vegetation and associated fuel dynamics. This model feature thus allows us to examine how climate change directly and indirectly affects prescribed fire planning and implementation while prior work only explored the former.

5 Conclusion

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We developed new forest management capabilities for the FATES vegetation demographic model, and then applied a new model benchmarking framework to assess if the model can accurately capture the key ecological processes that influence management outcomes in a fire-prone forest ecosystem. By implementing a prescribed fire model, adapting a logging model, and simulating treatment experiments at multiple sites in YPMC forests, we found that CLM-FATES adequately reproduced site observations of stand structure, size distribution, surface fuel load, and demography in response to prescribed burning and forest thinning, consistent with framework expectations. In addition, FATES also captures key differences in effect size and direction between prescribed fire and thinning and some aspects of interactions between treatment and site weather conditions, providing some confidence that the model can be used to investigate interactions between management scenarios and changing climate. While we only explored the effect of burn window parameters on prescribed fire outcomes in the model, projected change in climate is expected to further shrink burn windows, potentially constraining the feasibility and effectiveness of prescribed fire as a management tool (Swain et al. 2023). Understanding how the complex vegetation-climate-fire interactions will eventually alter landscape flammability to affect prescribed fire implementation can now be explored in this modeling framework. Further, the capability to simulate active forest management in an ESM context enables effects on surface-atmosphere carbon, water and energy exchange to be captured, as well as potential feedback to climate. However, we also identified two key processes that are currently missing and can affect model accuracy in projecting long-term ecosystem trends affected by management: insect outbreaks and the complex interactions between biotic and abiotic stressors, and surface fire to crown fire transitions under extreme fire weather and fuel conditions. Finally, standardized field measurements of key model parameters such as woody fuel turnover rate and plant allometry across a broader range of size classes for dominant plant functional types would enable further improvements to model fidelity and strengthen confidence in future projections. With ongoing model development and increasing field and remote sensing observations, we hope to address these questions in future work.

Data and Code Availability

The code and data used in this study are available at: https://github.com/XiulinGao/Sierra-mixedConifer-project; and FATES source code is available at https://doi.org/10.5281/zenodo.20787450.

Author contributions

XG, JK, CDK, and LMK formulated the idea. XG led the model development and modeling experiments with inputs from JK, CDK, LMK, and AHB. XG and JK led the data analysis and writing of the first draft with inputs from CDK and LMK. All authors contributed to the manuscript editing and finalization equally.

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Competing interests

The authors declare that they have no conflict of interests.

Disclaimer

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