Received: 2 November 2023 | Revised: 27 February 2024 | Accepted: 10 May 2024

DOI: 10.1002/eap.3023

ARTICLE

ECOLOGICAL APPLICATIONS
ECOLOGICAL SOCIETY OF AMERICA

Moderating effects of past wildfire on reburn severity depend on climate and initial severity in Western US forests

Claire M. Tortorelli | **Andrew M. Latimer** | **Derek J. N. Young**

Department of Plant Sciences, University of California, Davis, California, USA

Correspondence
Claire M. Tortorelli
Email: ctortorelli@ucdavis.edu

Present address
Claire M. Tortorelli, USDA Forest Service, Pacific Northwest Research Station, Corvallis, Oregon, USA.

Funding information
University of California Lab Fees Program; Hatch Project, Grant/Award Number: CA-D-PLS-2017-H

Handling Editor: Carolyn Hull Sieg

Abstract

Rising global fire activity is increasing the prevalence of repeated short-interval burning (reburning) in forests worldwide. In forests that historically experienced frequent-fire regimes, high-severity fire exacerbates the severity of subsequent fires by increasing prevalence of shrubs and/or by creating drier understory conditions. Low- to moderate-severity fire, in contrast, can moderate future fire behavior by reducing fuel loads. The extent to which previous fires moderate future fire severity will powerfully affect fire-prone forest ecosystem trajectories over the next century. Further, knowing where and when a wildfire may act as a landscape-scale fuel treatment can help direct pre- and post-fire management efforts. We leverage satellite imagery and fire progression mapping to model reburn dynamics within forests that initially burned at low/moderate severity in 726 unique fire pair events over a 36-year period across four large fire-prone Western US ecoregions. We ask (1) how strong are the moderating effects of low- to moderate-severity fire on future fire severity, (2) how long do moderating effects last, and (3) how does the time between fires (a proxy for fuel accumulation) interact with initial fire severity, day-of-burning weather conditions, and climate to influence reburn severity. Short-interval reburns primarily occurred in dry- and moist-mixed conifer forests with historically frequent-fire regimes. Previous fire moderated reburn severity in all ecoregions with the strongest effects occurring in the California Coast and Western Mountains and the average duration of moderating effects ranging from 13 years in the Western Mountains to >36 years in the California Coast. The strength and duration of moderating effects depended on climate and initial fire severity in some regions, reflecting differences in post-fire fuel accumulation. In the California Coast, moderating effects lasted longer in cooler and wetter forests. In the Western Mountains, moderating effects were stronger and longer lasting in forests that initially burned at higher severity. Moderating effects were largely robust to fire weather, suggesting that previous fire can mediate future fire severity even under extreme conditions. Our findings demonstrate that low- to moderate-severity fire buffers future fire severity in historically frequent-fire forests, underlining the importance of wildfire as a restoration tool for adapting to global change.

KEYWORDS
fire management, fire severity, forest resistance, moderating fire effects, reburn, restoration, self-regulation, Western United States, wildfire

INTRODUCTION

Warmer and drier climate conditions have led to an unprecedented increase in the frequency and number of large wildfires occurring across the globe (Abatzoglou & Williams, 2016), resulting in greater area experiencing "reburning," or burning multiple times in a relatively short period (Buma et al., 2020; Prichard et al., 2017). These fire regime shifts have raised concerns about forest loss where short-interval high-severity fire overwhelms forest mechanisms to resist change and recover following fire (Coop et al., 2020; Hagmann et al., 2021). Low- to moderate-severity fire, in contrast, can increase forest resistance to future fire by reducing fuel loads, especially in forests that historically experienced a frequent-fire regime (Collins et al., 2018; Hessburg et al., 2015; Prichard et al., 2017; Rodman et al., 2023). Understanding how strongly and for how long past fire moderates future fire behavior is key to accurately projecting future fire trajectories and adapting to global change (Abatzoglou et al., 2021; Prichard et al., 2017).

Restoring historic fire regimes and promoting forest resistance and resilience in the face of climate change is a management priority in the American West. Abundant dry-mixed conifer forests were historically maintained by frequent low-intensity fires, including indigenous cultural burning, but major socioecological transitions, including expulsion of many indigenous people and outlawing cultural burning (Taylor et al., 2016), together with nearly a century of active fire suppression has left forests overstocked, shifted species and size distributions, and modified fire regimes (Agee & Skinner, 2005; Hessburg et al., 2005). Fuel reduction treatments, including mechanical thinning and prescribed fire, can restore forest structure and increase forest resistance, but treatment limitations and the growing treatment backlog have prompted increased interest in using wildfire as a potential management alternative for reducing fire risk and restoring fire-excluded forest landscapes (Larson et al., 2022; North et al., 2021). Knowledge of how past fires and subsequent fuel buildup influence severity and burn patterns of future fires is therefore critical for understanding the state of fuels and fire risk in historically frequent-fire forests across western North America, and for informing decisions about where and when wildfire may help meet management goals (Greenler et al., 2023; Larson et al., 2022; Prichard et al., 2017; Rodman et al., 2023).

Studies of reburning in western forests consistently find that prior fire severity is a main driver of future fire severity: high-severity fire begets high-severity fire, and low- to moderate-severity fire moderates future fire severity (Harvey et al., 2016, 2023; Prichard et al., 2017; Taylor et al., 2021). While this pattern can partially be attributed to the persisting effects of topography and microclimates on fire behavior, it is also driven by fire and fuel feedbacks, including consumption of surface fuels, increased snags and downed wood, and changes in the abundance and continuity of shrubs which tend to increase reburn severity (Coop et al., 2020; Coppoletta et al., 2016). Reburn studies to date provide a valuable general theory of fire feedbacks but leave unanswered key questions about the generality, strength, and duration of moderating fire effects, particularly in cases when reburns following low- and high-severity initial fires (i.e., stands that remained forest and stands that converted to other vegetation types) are assessed together and potential interactions are not accounted for. Despite the focus of media headlines on megafire events that burn at uncharacteristically high severity, most of the burned area across the Western United States occurs at low- to moderate-severity (Johnstone et al., 2016; Reilly et al., 2017; Williams et al., 2023). To understand how today's forests, including those that have recently experienced fire, will respond to the contemporary increases in fire frequency and extent, it is therefore important to evaluate the drivers of reburn severity specifically in areas that remain forest after the preceding fire (Prichard et al., 2017).

The moderating effect of fire (i.e., the reduction in severity and/or occurrence of a future fire due to a past fire compared to once-burned areas) decreases in magnitude over time as understory fuels recover following fire (Cansler et al., 2022; Parks et al., 2014; Prichard et al., 2017; Rodman et al., 2023). The duration and strength of these effects can vary depending on various factors including climate, weather, and fuel consumption by the preceding fire, that is, previous fire severity (Figure 1) (Collins et al., 2018; Lydersen et al., 2017; Parks et al., 2015; Parks, Parisien, et al., 2018; Prichard et al., 2017).

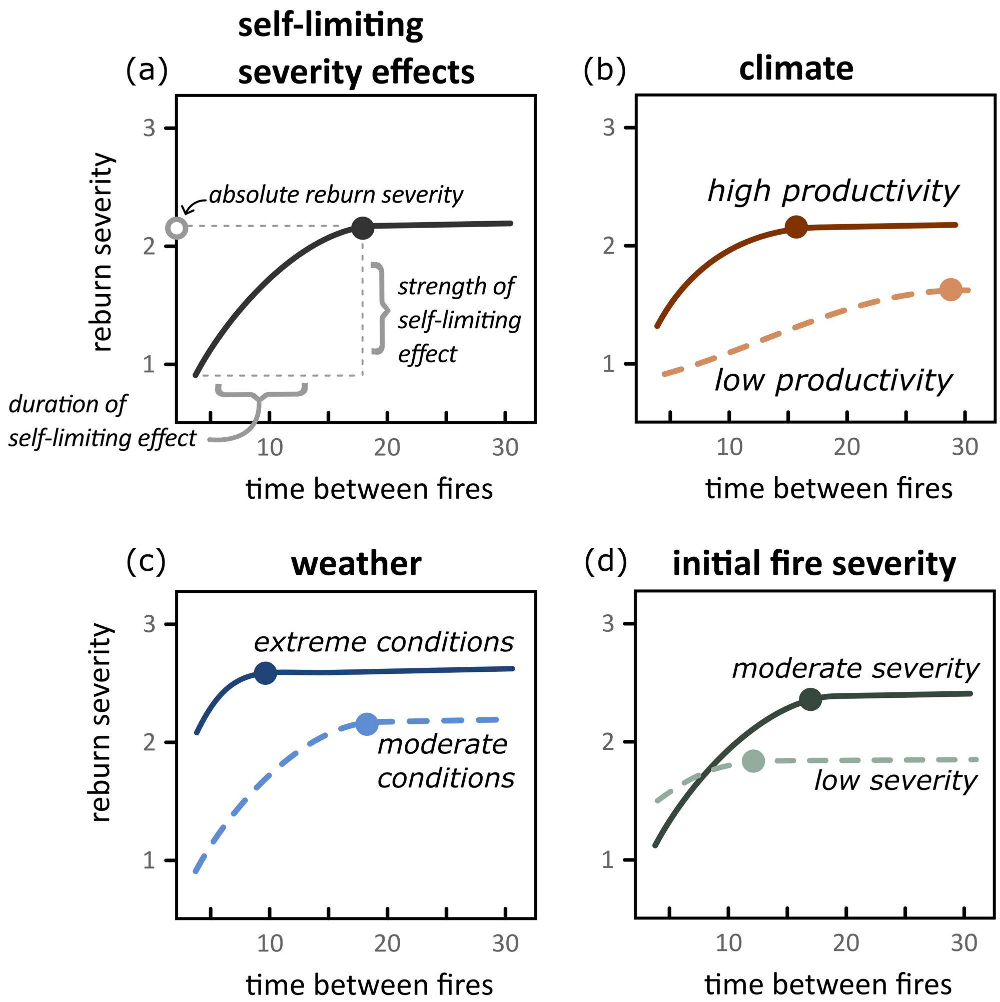

FIGURE 1 (a) Predicted reburn severity response to time between fires (a proxy for fuel accumulation). "Absolute reburn severity" is the predicted reburn severity measured at any time since fire. The "duration" of the moderating effect is the length of time between fires until the effect of time on reburn severity is reduced to ~0, indicated by a dot on the response curve. We measure the "strength" of moderating effects as the difference in absolute reburn severity at a 6-year fire return interval and absolute reburn severity at longer fire return intervals: 12 years (short term) and 24 years (long term). Panels (b)–(d) represent hypothesized relationships of time between fires and reburn severity under gradients of (b) climate, (c) fire weather, and (d) initial fire severity.

Precipitation and temperature gradients influence forest composition and site productivity and, consequently, the rate and magnitude of fuel buildup after fire (Figure 1b) (Parks, Parisien, et al., 2018). Severe fire weather can blunt moderating fire effects (Parks et al., 2015) (Figure 1c), especially in ecosystems with higher productivity where fire is more strongly constrained by fuel moisture and weather conditions than fuel amounts (Collins et al., 2019; Prichard et al., 2017). However, many examples exist where past fires maintained at least some moderating effects even under extreme conditions including drought, extreme heat, and plume-driven fire weather (Brodie et al., 2024; Lydersen et al., 2014; Prichard et al., 2017; Taylor et al., 2022). Previous fire severity and fuel consumption can also influence moderating effects (Parks et al., 2014). For example, low-severity fire that consumes primarily understory fuels can do less to increase forest resistance than moderate-severity fire where a greater proportion of canopy and ladder fuels are reduced, but enough canopy remains to inhibit a strong understory response (Greenler et al., 2023) (Figure 1d).

In this study, we perform the first cross-regional analysis of reburns in areas that remained forest after the initial fire to test how climate, weather, past fire, and the time between fires (a proxy for post-fire fuel accumulation) interact to influence reburn severity in predominantly frequent-fire forests of the Western United States (Figure 1). We ask (1) how strong are the moderating severity effects of low/moderate-severity fire, (2) how long do moderating effects last, and (3) how are moderating effects influenced by climate gradients, fire weather, and initial fire severity across four large fire-prone ecoregions.

METHODS

Our study encompasses forested areas within four large and fire-prone ecoregions of the Western United States: the Western Mountains (Sierra, Klamath, and Cascade Mountains), Northern Mountains (Blue Mountains and Northern Rockies), Southwest (Southern Rockies and Arizona-New Mexico Mountains), and California Coast (Figure 2a). Ecoregion delineation broadly follows Olson and Dinerstein (2002) and is consistent with other broad-scale analyses of wildfire drivers and patterns in western forests (Coop et al., 2022; Dennison et al., 2014; Parks & Abatzoglou, 2020). Forests in our study are predominantly dry- and moist-mixed conifer forests with a frequent-fire historical fire regime. We restricted our analyses to US National Forest lands to better account for pre- and post-fire management, as management actions are mapped and available in the US Forest Service Forest Activity Tracking System database (FACTS; USDA Forest Service, 2022).

Data

Fire data

We evaluated fire severity and number of times each pixel burned for large fires (>404 ha) that burned between 1986 and 2021. Fire perimeters were identified from the Monitoring Trends in Burn Severity (MTBS) program for areas that burned between 1986 and 2020 (Eidenshink et al., 2007). Fire perimeters that burned in 2021 were not yet incorporated into MTBS, so these were obtained from The Wildland Fire Interagency Geospatial Services database (National Interagency Fire Center, 2022). Duplicated fires were removed and overlapping fire perimeters within the same year were merged. Reburns were classified as areas that burned at least twice over the 36-year study period. The most recent and second most recent fires in each location are referred to as "reburn" and "initial" fires, respectively.

We identified initial fire and reburn severity at 30-m spatial resolution across the study fires using the composite burn index (CBI). CBI was estimated from corrected Landsat satellite imagery (Landsat-4:9) using correlations between remotely sensed indices and field-based fire severity measurements, which makes it a useful index for comparing burn severity across broad geographic regions (Key & Benson, 2006). CBI is a continuous index ranging from 0 (unburned/unchanged) to 3 (high severity/complete mortality; Table 1) (Key & Benson, 2006). We calculated CBI in Google Earth Engine (GEE) following Parks et al. (2019) based on the updated GEE script (2021). The number of times each pixel burned between 1986 and 2021 (burn count) and the number of years between the initial fire and reburn (time between fires) was evaluated using fire perimeter data and burn year attributes.

Fire weather predictors

To evaluate the role of daily weather on fire severity, we obtained the day-of-burn for each 30-m reburned pixel from interpolated satellite hotspot detections following the method presented by Parks (2014) incorporating hotspots detected by the Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) sensors as provided by the NASA Fire Information for Resource Management System (FIRMS). Fire weather was estimated by extracting c. 4-km resolution gridMET weather data to each pixel using bilinear interpolation (Abatzoglou, 2013). We extracted the day-of-burning vapor pressure deficit (VPD) in kilopascals and wind speed as measures of immediate fire weather. Day-of-burning energy release component (ERC) (Bradshaw et al., 1984) was selected to represent fuel moisture conditions at the time of burning. ERC is a composite fuel moisture index where higher values represent greater available energy released from fuels per unit area at the head of a fire's flaming front and greater potential fire intensity. Day-of-burning percentiles for fire weather variables were calculated for each pixel based on composited daily weather from 2002 to 2021.

Biophysical predictors

We considered topography, climate, vegetation, and management as potential predictors for our reburn severity models (Appendix S1: Table S1). Topographic position index (TPI) was calculated at the 2000-m scale using the "raster" package (Hijmans, 2022). Heat load was calculated from latitude, aspect, and slope following McCune and Keon (2002) at 30-m resolution using Digital Elevation Models obtained from LANDFIRE (LANDFIRE, 2019b). Average temperature and precipitation 30-year normals were extracted at 800-m resolution from PRISM data (PRISM Climate Group, 2022). Average annual actual evapotranspiration (AET) was extracted at 1000-m resolution from the University of Montana Numerical Terradynamic Simulation Group (Mu et al., 2014) as a proxy for potential site productivity. Biophysical Setting (BPS) from LANDFIRE (2019a) and tree cover at the time of reburning from the Rangeland Analysis Platform (2022) were used to determine vegetation type of reburned areas. Forest types were determined from reclassified BPS assignments (Appendix S1: Table S2).

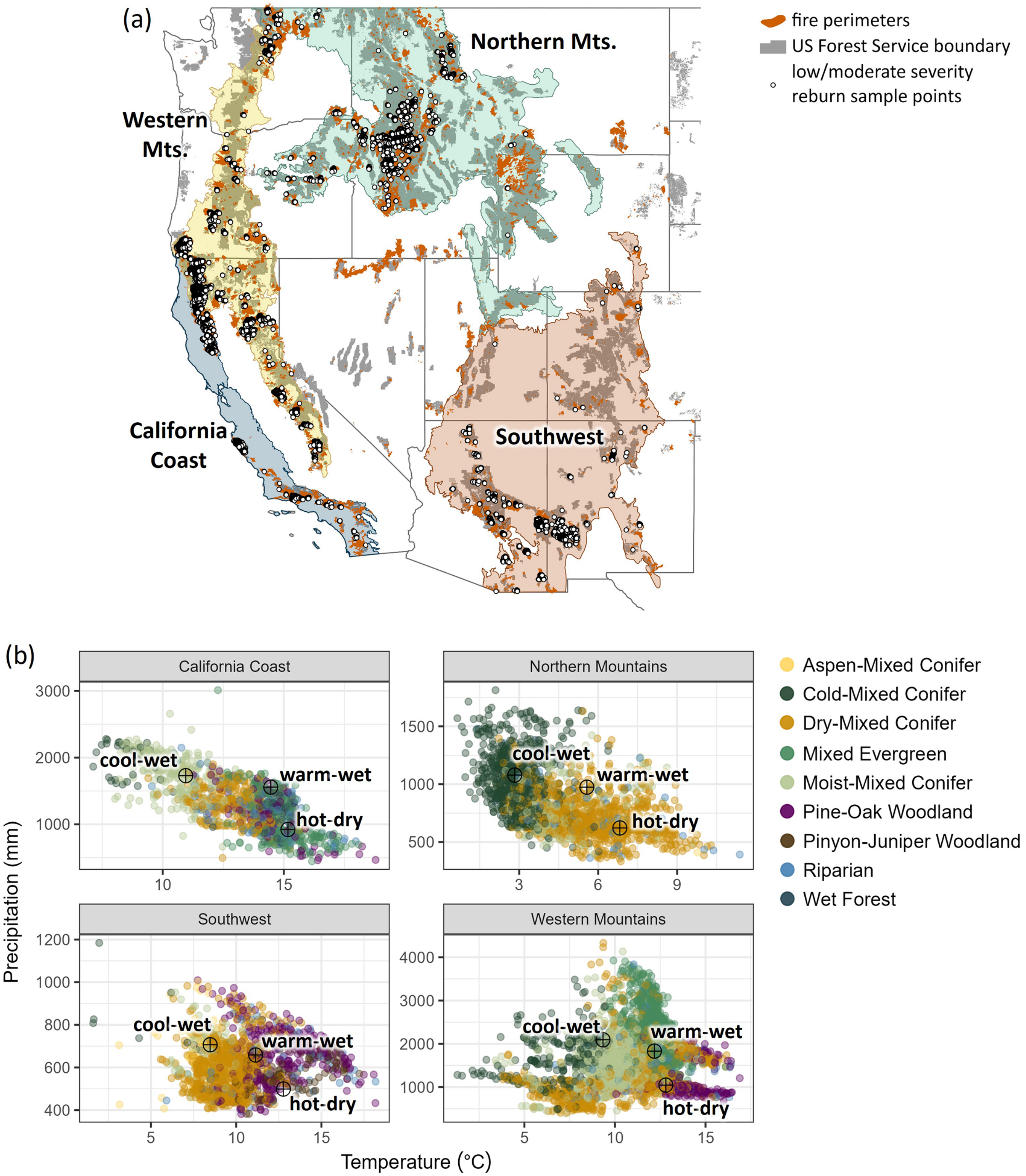

FIGURE 2 (a) Fire-prone study regions in the Western United States with locations of low/moderate-severity reburn sample points. Fire perimeters include only large fires (>404 ha) between 1986 and 2021 that intersect United States Forest Service boundaries. (b) Range of precipitation and temperature for reburned sample points by ecoregion colored by forest type. Points represent climate percentiles: "cool-wet" = 20th percentile of temperature and 80th percentile of precipitation; "warm-wet" = 70th percentile of temperature and 70th percentile of precipitation; "hot-dry" = 85th percentile of temperature and 20th percentile of precipitation.

TABLE 1 Conditional burn index (CBI) categories and description of severity effects following Key and Benson (2006).

Severity category	CBI	Description
Unchanged	0–0.1	Vegetation remained unchanged 1 year after fire
Low	0.1–1.24	Little mortality of intermediate or canopy trees
Moderate	1.25–2.24	Mixed effects ranging from unchanged to high. <60% overstory canopy mortality
High	2.25–3	High to complete canopy mortality

Fire Regime Groups were extracted from LANDFIRE BPS products (2019a).

Sample points

We selected pixels from reburned areas across the Western United States for our analyses using a gridded sampling approach. A rectangular grid of points with 270-m spacing was overlaid across reburned areas. Reburn severity, along with associated predictor data, were extracted to the point grid using nearest neighbor sampling. We filtered the resulting point grid based on the following six criteria. (1) Points were excluded from analysis if the most recent fire occurred prior to 2002 to correspond with the availability of MODIS satellite data and the ability to accurately measure daily fire spread (Parks, 2014). (2) To focus our analyses on areas that initially burned at low/moderate-severity, we limited our analysis to locations where initial fire severity (CBI) was >0.1 and <2.25. (3) To ensure that pixels within fire perimeters burned, we excluded pixels when reburn fire severity was ≤0.1. (4) We excluded points that fell within 300-m of a fire perimeter edge to limit the effect of perimeter mapping inconsistencies. (5) We restricted our analyses to forested areas by excluding points that had less than 30% tree cover at the time of reburning according to annual tree cover data extracted from Rangeland Analysis Platform products and/or were classified as a non-forest/woodland BPS. (6) We excluded areas that received fuel reduction treatments following the initial fire according to the FACTS database (<1% of total reburned pixels).

Statistical analyses

Variable selection

We used data from all ecoregions to inform our variable selection process. AET exhibited strong multicollinearity with precipitation and temperature ($r > 0.6$) and was removed from the final model (Appendix S1: Table S1). We chose not to include predictors representing pre-reburn vegetation cover and fuel amounts, as these are closely related to initial fire severity, time between fires, and climate variables. Additionally, we were primarily interested in how time between fires interacts with biophysical site characteristics to influence reburn severity in areas that remained forested after the initial fire, providing a potential proxy for fuel loads where understory fuels are not well represented with spectral imagery due to existing canopy cover. We explored including an interaction with forest type instead of climate in our models but chose to exclude this variable, despite its interpretability, because of extremely uneven sample sizes between forest types. Over half the sample points were classified as either dry- or moist-mixed conifer forest (Appendix S1: Figure S1). Additionally, we found that temperature and precipitation corresponded strongly with a gradient of dominant forest types in each region (Figure 2) and may better capture variation in understory productivity than broad forest type classifications. Our final models included 10 predictor variables: initial fire severity, burn count, time between fires, heat load, TPI, mean annual precipitation, mean annual temperature, and day-of-burn VPD, ERC, and wind speed percentiles (Appendix S1: Table S1). Predictor variables were centered and standardized by subtracting the mean and dividing by the standard deviation to facilitate model convergence.

Model fitting

We examined the interactive effects of time between fires and climate, weather, and previous fire characteristics on reburn severity using generalized additive models (GAMs). GAMs fit smoothing functions or splines which allowed us to model nonlinear relationships between variables while maintaining interpretability and the explicit testing of interactions (Hastie & Tibshirani, 1987; Wood, 2017). We evaluated how interactions between time since initial fire and abiotic predictors (precipitation, temperature, VPD, ERC, wind speed, and initial fire severity) influenced reburn severity by including multiple two-way tensor product interactions. Separate models were fit for each ecoregion with the same 10 predictor variables and six two-way interactions. GAMs were fit with cubic splines and normally distributed errors. All variables were included as smoothed terms, except "burn count," which was linear. To minimize overfitting and limit unrealistic response curves, we used moderately regularizing parameter settings—we fit GAMs with a gamma value of

1.4, maximum of five points of smoothing, and *select* set to "true" to allow coefficients to be shrunk towards zero (Marra & Wood, 2011). We tested autocorrelation of the residuals at different spatial lags using semi-variograms and found that sample point spacing of greater than 1-km limited spatial autocorrelation while maintaining a robust sample size for each ecoregion. We subsampled the dataset so that points were minimally spaced 1080-m apart using the "spThin" package in R (Aiello-Lammens et al., 2015), resulting in a final sample size of 8330 points from 881 distinct reburns (Table 2). Final models were fit on the thinned data. Restricted maximum likelihood (REML) was used to estimate smoothing parameters. We conducted analysis using the "mgcv" package (Wood, 2017) in R version 4.1.3 (R Core Team, 2022).

We displayed GAM results using partial dependence interaction plots to depict how time between fires interacted with climate, weather, and initial fire severity to influence reburn severity. For each set of predictions, all predictors except the interactions displayed were held at their means (0). Predictions span the minimum and maximum fire interval observed for each predictor group.

To evaluate the extent to which previous fire moderated future fire severity, we measured differences in predicted reburn severity from GAM output at different times since initial fire. To determine the "duration" of the moderating effects for each interaction level, we identified the minimum fire interval where the slope of the fitted spline function approached zero—the "flattening point" (i.e., the minimum time between fires when the first derivative of the fitted spline function fell between −0.05 and 0.05)—to indicate the fire return interval at which the initial fire no longer had a clear effect on predicted reburn severity (Figure 1). Derivatives of the fitted splines were calculated using the estimate_slopes function from the package "modelbased" (Makowski et al., 2020). We measured the "strength" of the moderating effect at two fire intervals to represent short- and long-term effects. "Short-term strength" was measured as the difference in predicted reburn severity between fire return intervals of 6 and 12 years. "Long-term strength" was measured as the difference in predicted reburn severity between fire return intervals of 6 and 24 years.

TABLE 2 Reburn sample size by region.

Ecoregion	Unique fire event pairs (reburns)	Reburn sample points (*n*)
California Coast	74	1217
Northern Mountains	322	1859
Southwest	216	1412
Western Mountains	269	3842

We chose a 6-year interval as the baseline for comparison because this is the low end of the historical range of variability for many of our reburn sample points and all ecoregions had sufficient data between fire return intervals of 6 and 24 years for comparison.

RESULTS

Ecoregion overview

Across the four ecoregions, the majority of our low/moderate-severity reburned sample points were classified as dry- or moist-mixed conifer forests with historically low-severity, frequent-fire regimes (Appendix S1: Figure S1). However, gradients of climate, productivity, and forest composition still existed within and between ecoregions (Figure 2b; Appendix S1: Figures S1 and S2). The Western Mountains and California Coast encompassed the widest range of mean precipitation and temperatures and were generally the most productive, composed primarily of moist-mixed conifer, dry-mixed conifer, and mixed evergreen forests (Figure 2b; Appendix S1: Figures S1 and S2). On average, reburned areas in the Southwest were the driest, supporting mostly dry-mixed conifer, pine-oak, and pinyon-juniper woodlands (Figure 2b; Appendix S1: Figure S2). Northern Mountains were the coolest with the highest proportion of cold-mixed conifer forest (Figure 2b; Appendix S1: Figure S2).

The four ecoregions displayed different patterns of reburn severity and predictor variable distributions (Figure 3). On average, absolute reburn severity following low/moderate-severity fire was the highest in the Western Mountains and California Coast and lowest in the Southwest (Figure 3a). The California Coast had the highest proportion of sample points that reburned at high severity (CBI > 2.24) after initially burning at low/moderate-severity (32.6%), followed by the Western Mountains (30.8%) and the Northern Mountains (29.6%). The Southwest had the lowest proportion with only 8.4% of sample points reburning at high severity. Initial CBI from low/moderate-severity fires was also generally highest in the California Coast and lowest in the Southwest (Figure 3d). Median time between low/moderate-severity fire and reburns was relatively consistent between ecoregions, ranging from 11 years in the Southwest to 15 years in the Western Mountains and California Coast. However, the distribution of time between fires varied by ecoregion (Figure 3b). Day-of-reburn wind speeds were slightly higher in the Southwest than in other ecoregions (Figure 3e). ERC and VPD distributions were highly left-skewed with nearly all reburns occurring under days when ERC and VPD percentiles exceeded 75%

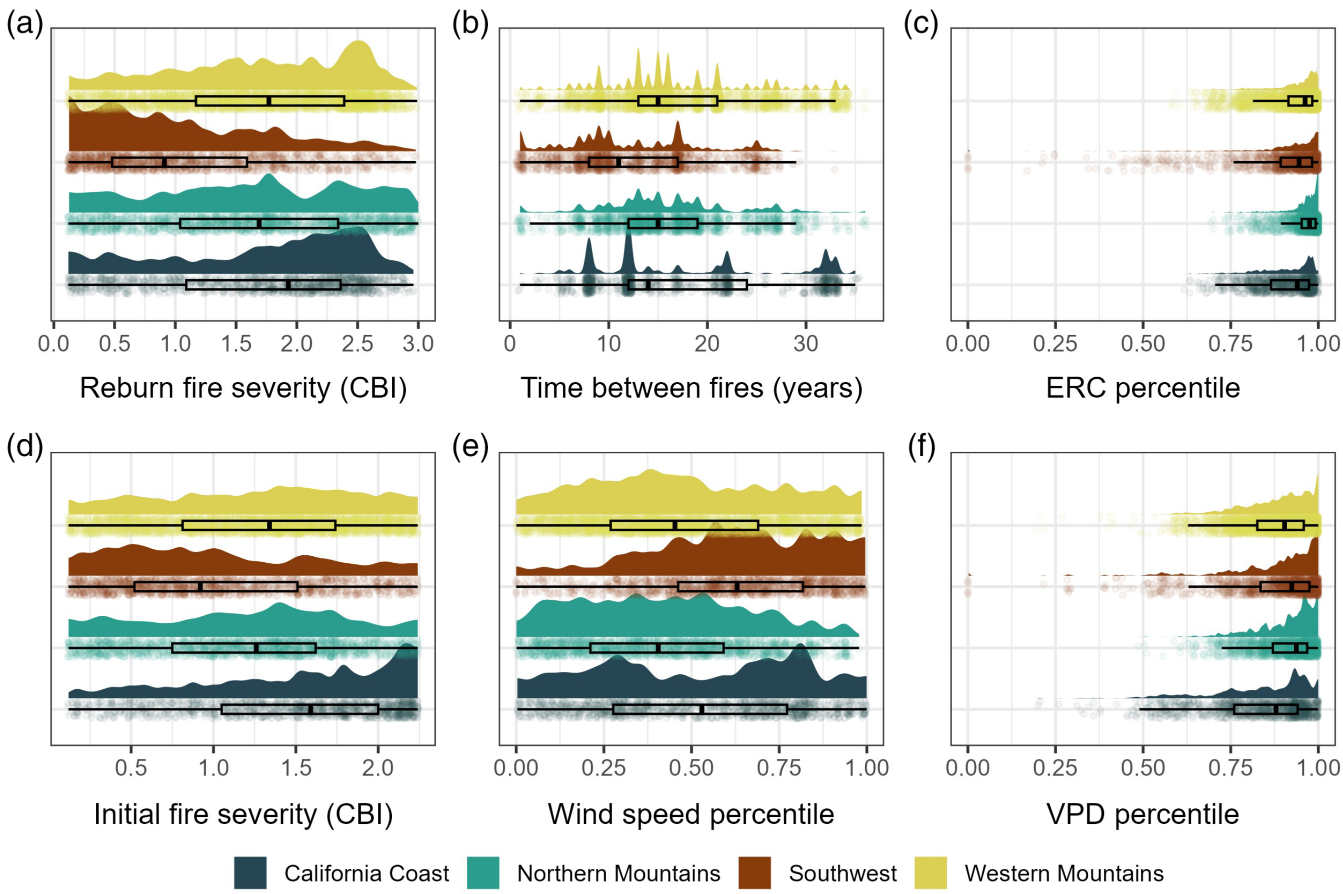

FIGURE 3 Distribution of reburn sample points for (a) reburn fire severity, (b) years between initial fire and reburn, (c) day-of-burning energy release component (ERC), (d) initial fire severity, (e) day-of-burning wind speed, and (f) day-of-burning vapor pressure deficit (VPD). CBI, composite burn index.

(Figure 3c,f), corresponding with typical fire season weather.

Effect of fire interval on reburn severity varies by ecoregion

Overall, absolute reburn severity increased with time between fires in all ecoregions. However, the strength and duration of the moderating effects varied strongly by region and with some biophysical predictors (Appendix S1: Table S3). After accounting for topography, climate, weather, and initial fire severity by holding these predictors at their means, we identified a temporal duration of the moderating effects (i.e., a "flattening point"; see *Methods*) for all ecoregions except the California Coast. On average, the duration of moderating effects was the shortest in the Western Mountains, where the initial effect of previous low/moderate-severity fire on reburn severity flattened after 13 years. Predicted reburn severity increased at a slower rate between 17 and 29 years before flattening a second time (Appendix S1: Figure S3). The duration of moderating effects was substantially longer in the Southwest (19 years) and Northern Mountains (25 years), though reburn severity continued to increase slightly after flattening for the duration of the observation period in these ecoregions. In the California Coast, moderating effects did not substantially level off during the 36-year observation period (Appendix S1: Figure S3).

The strength of moderating effects varied substantially by ecoregion and time between fires. Across all fire return intervals, the California Coast had the strongest moderating effects on average, and the Northern Mountains had the weakest moderating effects. Previous low/moderate-severity fire had the strongest short-term moderating effect in the California Coast and Western Mountains where predicted reburn CBI was 0.37 and 0.25 higher (34.5% and 18.8% higher), respectively, when reburns occurred 12 years following the initial fire opposed to 6 years. Short-term moderating effects were weaker in the Southwest and Northern Mountains where reburn CBI at a 12-year fire interval was 0.19 and 0.13 higher (28.5% and 9.2% higher), respectively, than at a 6-year fire interval. The California Coast had the strongest long-term moderating effects—CBI was 0.68 (63.5%) higher when reburns occurred 24 years after the initial fire than when reburns occurred after 6 years. Model fit varied by ecoregion with 36% deviance explained in the California Coast, 30% in the Southwest, 32% in the Northern Mountains, and 20% in the Western Mountains (Appendix S1: Table S3).

Biophysical factors influence moderating severity effects

Climate influenced absolute reburn severity and the effect of fire interval on reburn severity differently depending on ecoregion. In the California Coast, hot-dry and warm-wet forests (predominantly dry-mixed conifer and mixed evergreen, respectively) generally reburned at higher absolute severity than cool-wet forests (mostly moist-mixed conifer), after controlling for topography, initial fire severity, and reburn fire weather (Figure 4). This pattern was also present in the Western Mountains, although the climate effect was not as strong (Figure 4). Of the biophysical factors included in our models, climate interacted the most consistently with time between fires to influence reburn severity. All ecoregions except the Southwest demonstrated strong interactions between temperature and time between fires, and precipitation interacted strongly with time between fires in both the Northern Mountains and Southwest (Appendix S1: Table S3). In cool-wet forests of the California Coast, reburn severity continued to increase over the entire observation period (36 years), demonstrating a much longer lasting moderating effect than in warmer forests, where the effect diminished 22 years after the initial fire (Figure 4). We observed the opposite trend in the Northern Mountains, where cool-wet forests (predominantly cold-mixed conifer) reburned at the highest severity regardless of fire interval, and hot-dry (mostly dry-mixed conifer)

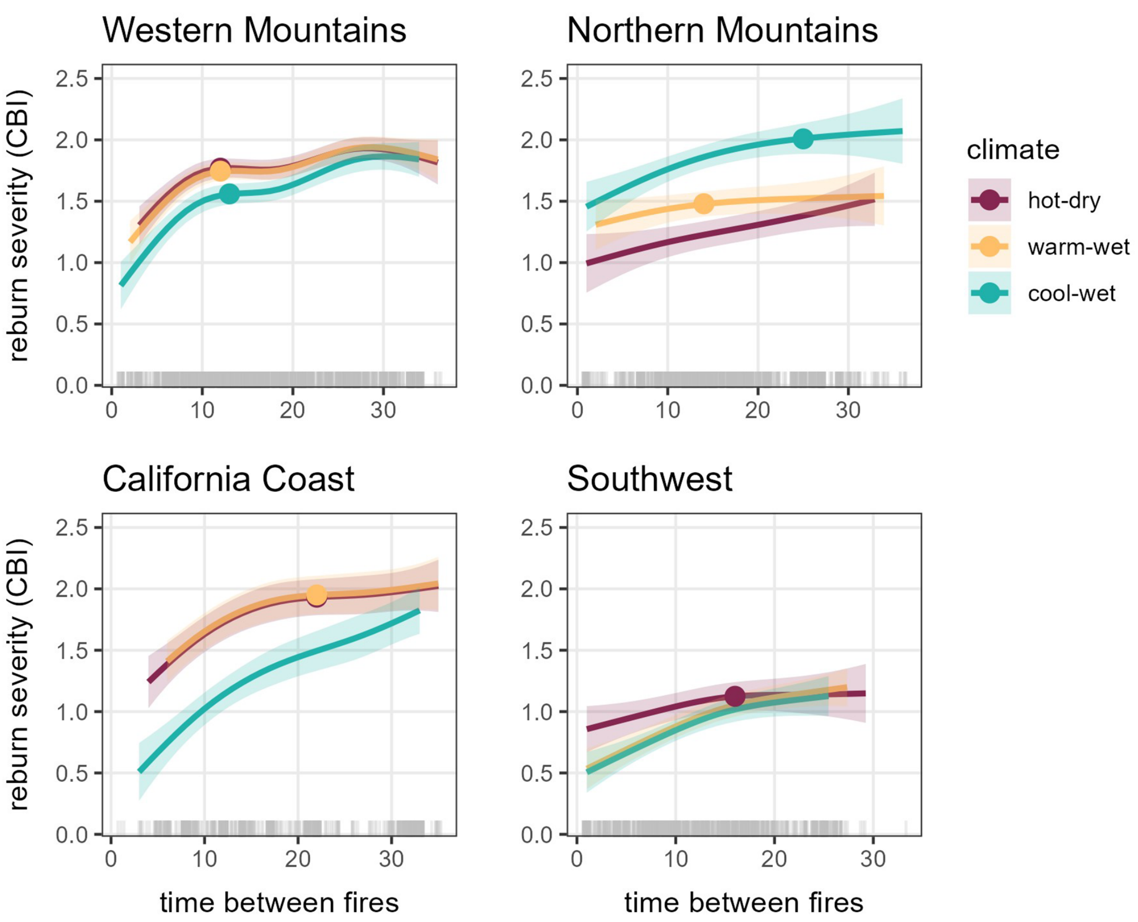

FIGURE 4 Predicted reburn severity response to time between fires and climate by ecoregion with 95% CIs. Points indicate the duration of the moderating severity effects (i.e., the minimum time between fires when the first derivative of the fitted spline function fell between −0.05 and 0.05). Climate categories were determined based on temperature and precipitation quantiles for each ecoregion: "cool-wet" = 20th percentile of temperature and 80th percentile of precipitation; "warm-wet" = 70th percentile of temperature and 70th percentile of precipitation; "hot-dry" = 85th percentile of temperature and 20th percentile of precipitation. CBI, composite burn index.

forests exhibited longer lasting moderating effects (>33 years) than cool-wet forests where the effects diminished 25 years after the previous burn (Figure 4). We observed relatively weak moderating effects in warm-wet forests of the Northern Mountains (a mix of moist- and dry-mixed conifer forests) and in hot-dry forests in the Southwest (predominantly pine-oak and pinyon-juniper woodlands). In the Southwest, hot-dry forests had slightly higher absolute reburn severity than cooler and moister forests (characterized by dry- and moist-mixed conifer) at shorter fire return intervals, but the effect diminished after 16 years, whereas reburn severity continued to increase across the observation period in wetter forests (Figure 4).

Absolute reburn severity was consistently higher at higher wind speeds and more extreme weather conditions in all ecoregions except the Northern Mountains (Appendix S1: Table S3). In contrast to our expectations, day-of-burning weather conditions did not strongly interact with fire interval to influence reburn severity in most ecoregions. However, in the Northern Mountains, more extreme VPD and ERC corresponded with slightly weaker short-term moderating effects (Figure 5; Appendix S1: Table S3). In contrast, forests that reburned at higher wind speeds displayed slightly stronger and longer lasting moderating effects than areas that burned at low to moderate wind speeds in the Northern Mountains and Southwest (Figure 6).

In all ecoregions, absolute reburn severity was higher in forests that initially burned at moderate severity than low severity regardless of fire interval (Figure 7; Appendix S1: Table S3). Initial severity interacted with time between fires to influence reburn severity in only the Western Mountains and Southwest. Notably, in the Western Mountains, the effect duration was 4 years longer and the 12-year moderating effect was 87.3% higher in forests that previously burned at moderate severity (CBI = 2.0) compared with those burned at low severity (CBI = 0.5) (Figure 7). Similarly, in the Southwest, reburn severity flattened after 16 years in areas

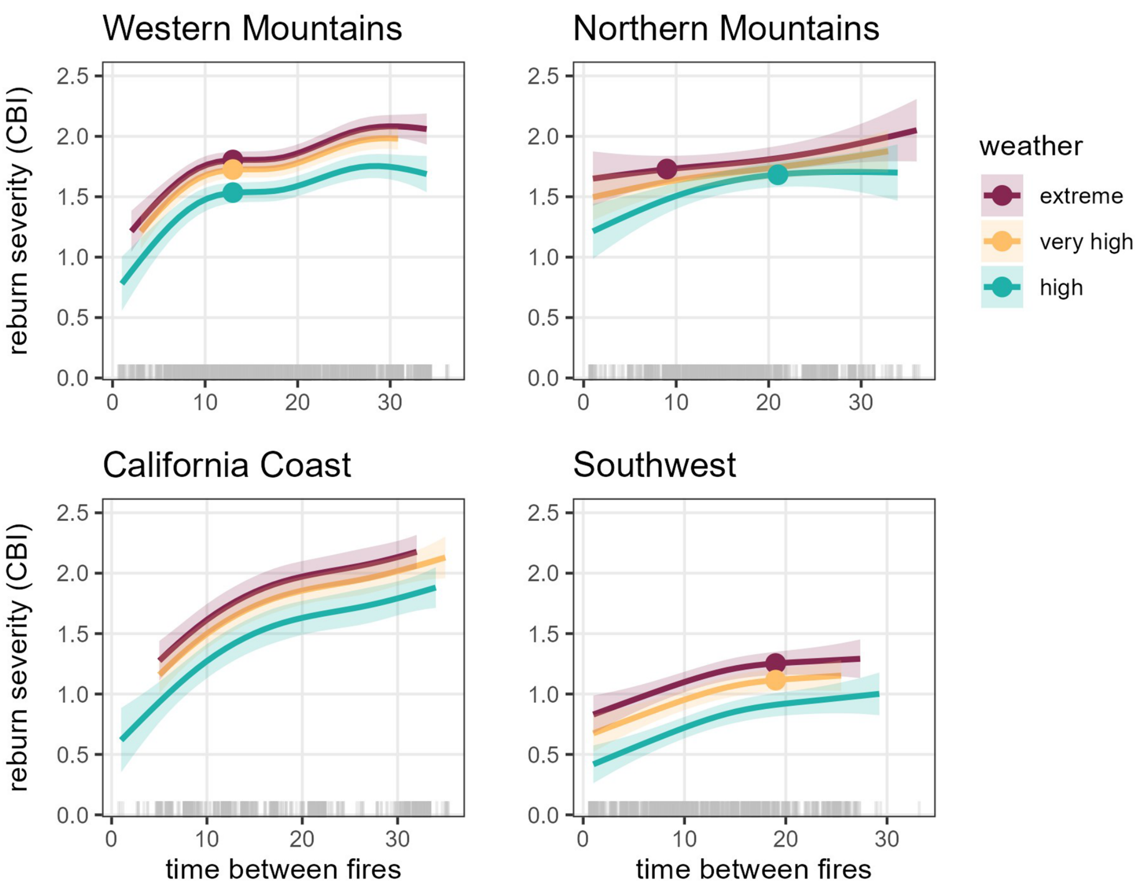

FIGURE 5 Predicted reburn severity response to time between fires and day-of-burning weather by ecoregion with 95% CIs. Points indicate the duration of the moderating severity effects (i.e., the minimum time between fires when the first derivative of the fitted spline function fell between −0.05 and 0.05). Weather categories were determined based on energy release component and vapor pressure deficit percentiles for each sample point: "extreme" = 98th percentile; "very high" = 95th percentile; "high" = 85th percentile. CBI, composite burn index.

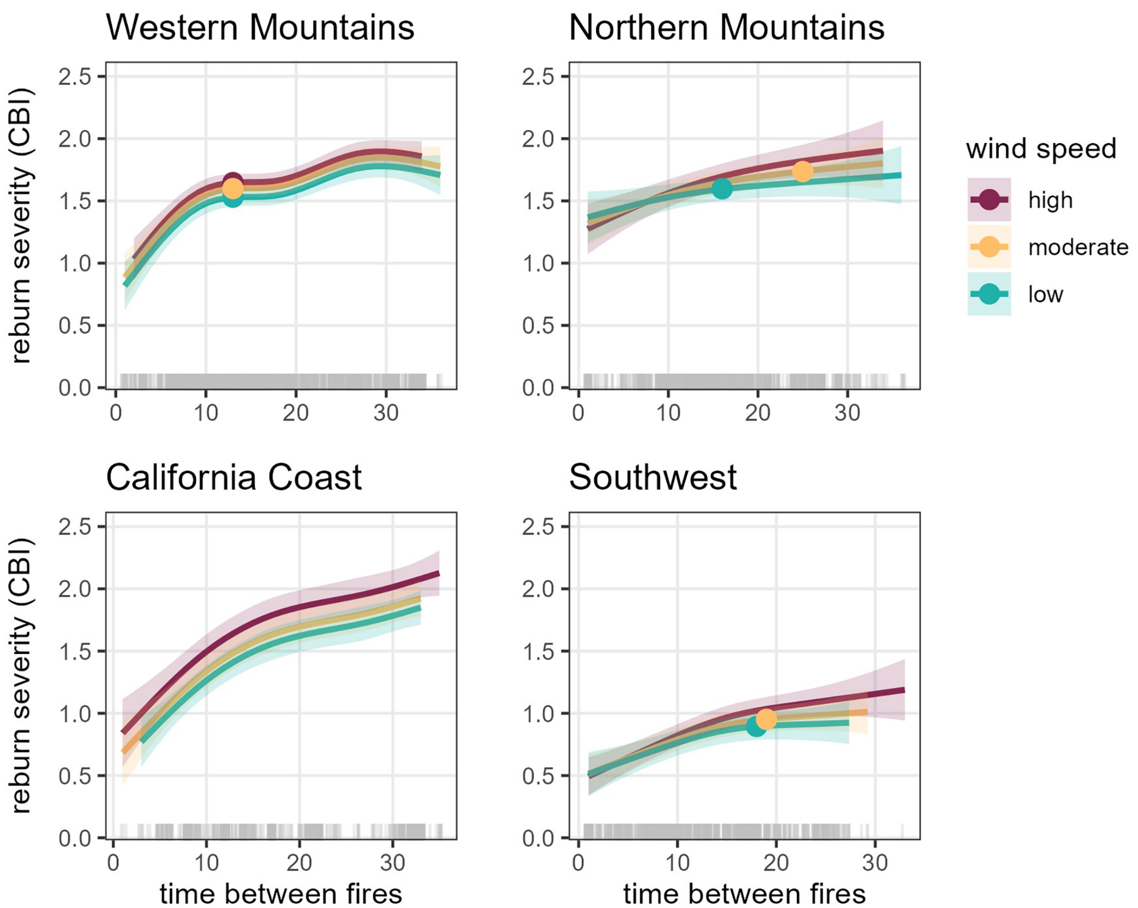

FIGURE 6 Predicted reburn severity response to time between fires and wind speed by ecoregion with 95% CIs. Points indicate the duration of the moderating severity effects (i.e., the minimum time between fires when the first derivative of the fitted spline function fell between −0.05 and 0.05). Wind speed categories were determined based on wind speed percentiles for each sample point: "high" = 95th percentile; "moderate" = 50th percentile; "low" = 25th percentile. CBI, composite burn index.

initially burned at low severity, while continuing to increase after 10 years in forests initially burned at moderate severity (Figure 7). Across fire intervals, predicted reburn severity was generally higher than initial severity when severity was low, and below or near initial severity when reburn severity was moderate (Figure 7). This observation is likely primarily a sampling artifact: initial fire was constrained to low/moderate severity, whereas we did not constrain the severity of the reburn.

DISCUSSION

Wildfire (and consequently reburning) is projected to become more prevalent in coming decades (Abatzoglou et al., 2021), highlighting the importance of ecological legacies and fire feedbacks for the future of fire-prone ecosystems. Our results show that previous low- to moderate-severity fire consistently buffers future fire severity, and the strength of these moderating effects decrease with increasing time since the initial burn. These findings are consistent with concepts of wildfire self-regulation through fuel consumption and the decrease over time of moderating effects as fuels build up following the previous fire (Buma et al., 2020; Cansler et al., 2022; Parks et al., 2014; Prichard et al., 2017). Although previous fires mediated reburn severity in all ecoregions, we observed substantial differences in the strength and duration of moderating effects between geographical regions and along some biophysical gradients, likely driven by variability in post-fire vegetation composition and productivity. Moderating effects were mostly robust, however, to day-of-burning weather suggesting that previous low/moderate-severity fire can moderate future fire severity even under extreme weather conditions.

The strength and duration of moderating effects vary by ecoregion

The strength and duration of moderating effects varied substantially between ecoregions. The strongest short-term

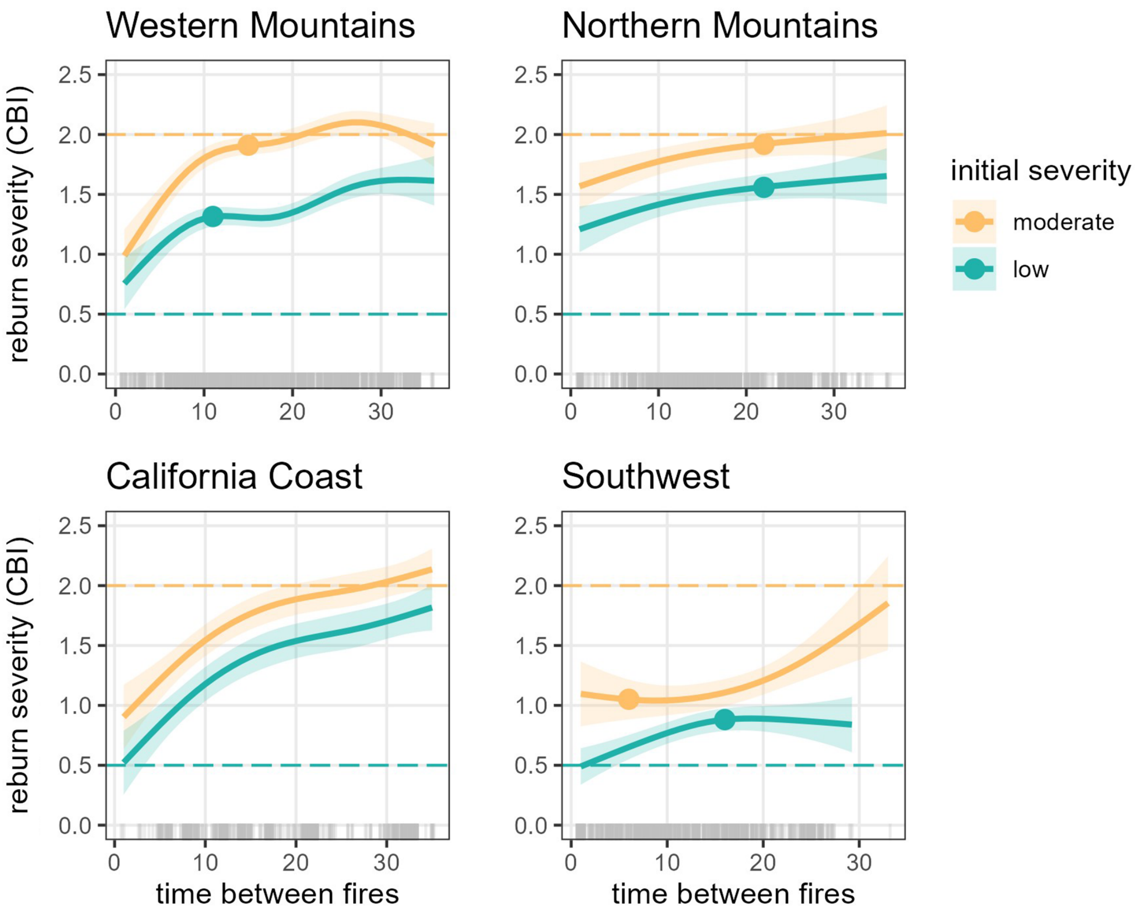

FIGURE 7 Predicted reburn severity response to time between fires and initial fire severity by ecoregion with 95% CIs. Points indicate the duration of the moderating severity effects (i.e., the minimum time between fires when the first derivative of the fitted spline function fell between −0.05 and 0.05). Initial fire severity composite burn index (CBI) classes: "low" = 0.5; "moderate" = 2.0. Dashed lines depict initial fire severity for reference.

effects occurred in the California Coast and Western Mountains, with weaker, but relatively long-lasting effects in the Northern Mountains and Southwest. In the California Coast, the duration of the moderating effect exceeded our 36-year observation window, suggesting long-term fuel recovery following low/moderate-severity burns in this region. Alternatively, the strong but shorter lived effects in the Western Mountains could be attributed to overall high productivity and rapid rates of fuel buildup in frequent-fire forests within this ecoregion. For example, understory and ladder fuels far exceeded prefire levels 8 years after low-severity prescribed fire in Sierra mixed conifer forests (Chiono et al., 2012; Vaillant et al., 2013). Observed effect durations in the Western and Northern Mountains were consistent with a review of reburn dynamics which found that previous fires moderated reburn severity and spread for 7–22 years in Rocky Mountain and Sierra mixed conifer study ecoregions (Prichard et al., 2017). We observed longer lasting moderating effects in the Southwest than previous studies, which reported effects fading 10–15 years in this region (Prichard et al., 2017; Rodman et al., 2023). These mixed results may be attributed to differences in study scope: previous studies included forests that initially burned at high severity and may have been dominated by dense young trees or were no longer forested at the time of reburning, complicating severity comparisons (Saberi & Harvey, 2023). Including high-severity reburns likely reduces the overall observed strength and duration of moderating effects, given that dense regenerating forests, pyrogenic shrubs, and grasses respond quickly to canopy loss and these vegetation types nearly always reburn at high severity (Agne et al., 2023; Coop et al., 2020; Coppoletta et al., 2016; Kerns et al., 2020; Tortorelli et al., 2023; Turner et al., 2019).

Biophysical factors influence moderating effects

Of the biophysical factors we examined in our models, climate interacted with time between fires to influence reburn severity the most consistently across ecoregions. In the Northern Mountains, cool-wet forests (mostly cold-mixed conifer) generally reburned at higher severity and had slightly stronger and shorter lived moderating effects than hot-dry forests, consistent with findings in the Northern Rocky Mountains and Sierra Nevada (Cansler et al., 2022; Steel et al., 2015). Cold-mixed conifer forests recover quickly after a single fire when canopy openings promote dense regeneration of conifers (Turner et al., 2019), potentially limiting how long previous fires moderate future fire severity. In contrast, short interval fires in less productive dry-mixed conifer forests are more strongly limited by fuel availability than fuel moisture, resulting in longer lasting moderating effects when the canopy remains intact after the initial fire and understory vegetation is slow to recover (Steel et al., 2015). Previous fires did little to buffer reburn severity in warm-wet Northern Mountains climates. Fire in these highly productive forests may be more strongly limited by fuel moisture and ignitions than fuel amounts, and reburn severity could depend more on interannual climate fluctuations than fuel reductions from previous burns (Krawchuk & Moritz, 2011). In the California Coast and Southwest, shorter lived moderating effects in hot-dry climates (e.g., pine-oak woodlands) were likely due to strong regrowth and rapid fuel buildup of flammable invasive grasses and/or resprouting oaks after burning, limiting the duration of moderating fire effects (Keeley et al., 2005; Pausas & Keeley, 2017; Yocom et al., 2022). Our findings provide insights into the rate and magnitude of fuel buildup after initial fires at broad spatial scales, but additional research is needed on vegetation recovery following low- to moderate-severity fires in the field to better understand how species composition and structure influence the extent to which previous fires moderate reburn severity.

Absolute reburn severity was consistently higher under more extreme fire weather conditions. This was expected given that higher wind speeds, higher temperatures, and lower relative humidity are consistently associated with higher fire severity across Western US forests (Parks, Holsinger, et al., 2018). Fire weather did not, however, strongly influence the strength or duration of moderating severity effects. This finding is consistent with observations of previous fire blunting high-severity effects of subsequent fires even under extreme fire weather (Brodie et al., 2024; Lydersen et al., 2014; Prichard et al., 2017; Taylor et al., 2022). The 2021 Dixie fire in California mixed conifer forests provided a dramatic example of the potential for previous low-severity fire to buffer fire effects within a plume-driven megafire (Taylor et al., 2022). Alternatively, there are many examples of extreme weather conditions completely overriding or substantially reducing the buffering effect of previous burns on subsequent fire spread and severity (Collins et al., 2009; Parks et al., 2014, 2015). These mixed results may stem from differences in the range of observed reburn weather conditions. Fire suppression is more effective under mild and moderate weather conditions, contributing to few reburns occurring during periods of milder weather on actively managed United States Forest Service land. Thus, we may have observed less variability in moderating effects than studies focused on Wilderness areas (e.g., Parks et al., 2014) where fires are generally not suppressed.

Our findings corroborate many studies in demonstrating a strong ecological memory of fire (Coppoletta et al., 2016; Prichard et al., 2017; Taylor et al., 2021). Initial fire severity was a strong predictor of reburn severity in all regions, with areas that initially burned at higher severity generally reburning at higher severity. Our focus on initial fires that burned at low to moderate severity allows us to investigate the nuances of this relationship without the complication of interpreting reburn severity following a stand replacing fire, when a previously forested area is dominated by young trees, shrubs, and/or grass at the time of the reburn (Holden et al., 2010; Saberi & Harvey, 2023). As expected, in the Western Mountains, we observed stronger and longer lasting moderating effects in forests that initially burned at moderate severity. Similarly, in the Southwest, long-term moderating effects were much stronger in forests that previously burned at moderate severity. Moderate-severity fire consumes woody understory and ladder fuels, often without catalyzing high growth of pyrogenic shrubs, increasing forest resistance to future fire (Greenler et al., 2023; Larson et al., 2013; Stevens-Rumann & Morgan, 2016). In contrast, low-severity fire removes primarily understory and herbaceous fuels that recover quickly after fire and generally does less to restore forest structure and composition (Greenler et al., 2023; Larson et al., 2013). Surprisingly, the duration of moderating effects was robust to differences in initial fire severity in the Northern Mountains and California Coast, suggesting that rates of fuel buildup are similar regardless of vegetation consumption in the initial fire (when at least 30% forest canopy is left intact). Notably, areas that burned at low initial fire severity displayed moderating effects in all regions, demonstrating that small reductions in fuel loads can buffer future fire behavior even in the absence of larger changes to forest structure or composition.

Management implications

Across the Western United States, wildfires are much more abundant and cover larger areas than fuel treatments and prescribed burns (North et al., 2021; Stevens et al., 2021). From 2010 to 2020 in California, more than three times as much area burned in low- to moderate-severity wildfire than was treated using mechanical thinning or prescribed burning (North et al., 2021). Our study demonstrates that previous low- to moderate-severity fires can buffer reburn severity for at least a decade in all regions, even under variable climates and extreme weather conditions. However, buffering effects mostly fade after less than two decades, suggesting that relatively short management intervals (e.g., <12 years in the Western Mountains) may be necessary to reduce future fire severity, and the duration of treatment effects will likely vary with vegetation composition, site productivity, and previous fire severity. These findings reflect recent work that suggests that fuel reduction treatments should be implemented on a <10-year interval to meaningfully reduce severe fire risk in a closed-cone pine forest in California (Agne et al., 2023). Forests that burned in the last 10–20 years at low/moderate severity could be transitioned to an active treatment schedule and/or be targeted for additional thinning to maintain and improve resistance with lower initial investment (Greenler et al., 2023; North et al., 2021; Stevens et al., 2021). Fewer than 1% of our reburn sample sites received fuel treatments following the initial fire, demonstrating abundant opportunities to further harden burned areas to future fires and direct composition and structure towards desired conditions.

Our study provides useful insights into the drivers of moderating fire effects across large regions. However, additional studies are needed to better understand how local variations in vegetation composition and post-fire fuel buildup influence reburn severity at finer-scales in areas that initially burned at low/moderate severity. This is particularly urgent given that there currently exists no way to monitor understory surface fuel loads directly at fine resolution over large areas, given that forest canopy obstructs views from satellite and aeriel imagery. As our study was focused primarily on large wildfires, our results may not accurately represent moderating effects resulting from small-scale prescribed burning, especially those that occur under mild weather conditions and result in little to no canopy loss (Greenler et al., 2023).

CONCLUSIONS

The continued rise in global fire activity highlights the need to better understand the extent to which past burns mediate future fire in fire-prone ecosystems. Our analyses demonstrate that previous low- and moderate-severity fires mitigate future fire behavior across primarily frequent-fire Western US forests, but that the strength and duration of moderating effects vary substantially by ecoregion and along biophysical gradients, including climate and previous fire severity, within some ecoregions. Across all regions, moderating effects were mostly robust to fire weather, suggesting that previous fire can buffer future fire severity even under extreme conditions. However, moderating effects faded relatively quickly (in less than two decades) in most cases. These findings improve our understanding of fire feedbacks and enable better projections of future fire trajectories and risk. By demonstrating when, where, and for how long previous fires buffer future fire severity, our results can inform management decisions to help meet restoration goals and adapt to global change.

AUTHOR CONTRIBUTIONS

Claire M. Tortorelli compiled data and wrote the initial draft. Derek J. N. Young and Claire M. Tortorelli performed the analysis. All authors contributed to study questions, discussed the analytical approach and results, and made comments on the manuscript.

ACKNOWLEDGMENTS

We thank Sean Parks for sharing daily fire spread data and code and Michael Kootz and Lisa Rosenthal for analytical assistance. Skye Greenler provided valuable feedback on management implications. We would also like to thank the Gordon and Betty Moore Foundation. This work was supported by funding from the University of California Lab Fees Program and from Hatch Project CA-D-PLS-2017-H.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data and code (Tortorelli & Young, 2024) are available in Zenodo at https://doi.org/10.5281/zenodo.11490965.

ORCID

Claire M. Tortorelli https://orcid.org/0000-0001-9493-9817
Andrew M. Latimer https://orcid.org/0000-0001-8098-0448
Derek J. N. Young https://orcid.org/0000-0003-2465-0254

REFERENCES

Abatzoglou, J. T. 2013. "Development of Gridded Surface Meteorological Data for Ecological Applications and Modelling." *International Journal of Climatology* 33(1): 121–131. https://doi.org/10.1002/joc.3413.

Abatzoglou, J. T., D. S. Battisti, A. P. Williams, W. D. Hansen, B. J. Harvey, and C. A. Kolden. 2021. "Projected Increases in

Western US Forest Fire despite Growing Fuel Constraints." *Communications Earth & Environment* 2(1): 227. https://doi.org/10.1038/s43247-021-00299-0.

Abatzoglou, J. T., and A. P. Williams. 2016. "Impact of Anthropogenic Climate Change on Wildfire across Western US Forests." *Proceedings of the National Academy of Sciences of the United States of America* 113(42): 11770–75. https://doi.org/10.1073/pnas.1607171113.

Agee, J. K., and C. N. Skinner. 2005. "Basic Principles of Forest Fuel Reduction Treatments." *Forest Ecology and Management* 211(1–2): 83–96. https://doi.org/10.1016/j.foreco.2005.01.034.

Agne, M. C., J. B. Fontaine, N. J. Enright, S. M. Bisbing, and B. J. Harvey. 2023. "Rapid Fuel Recovery after Stand-Replacing Fire in Closed-Cone Pine Forests and Implications for Short-Interval Severe Reburns." *Forest Ecology and Management* 545: 121263. https://doi.org/10.1016/j.foreco.2023.121263.

Aiello-Lammens, M. E., R. A. Boria, A. Radosavljevic, and B. Vilela. 2015. "spThin: An R Package for Spatial Thinning of Species Occurrence Records for Use in Ecological Niche Models." *Ecography* 38(5): 541–545. https://doi.org/10.1111/ecog.01132.

Bradshaw, L. S., J. E. Deeming, R. E. Burgan, and J. D. Cohen. 1984. *The 1978 National Fire-Danger Rating System: Technical Documentation*, Vol. 169. Ogden, UT: US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Brodie, E. G., E. E. Knapp, W. R. Brooks, S. A. Drury, and M. W. Ritchie. 2024. "Forest Thinning and Prescribed Burning Treatments Reduce Wildfire Severity and Buffer the Impacts of Severe Fire Weather." *Fire Ecology* 20(1): 17. https://doi.org/10.1186/s42408-023-00241-z.

Buma, B., S. Weiss, K. Hayes, and M. Lucash. 2020. "Wildland Fire Reburning Trends across the US West Suggest Only Short-Term Negative Feedback and Differing Climatic Effects." *Environmental Research Letters* 15(3): 034026. https://doi.org/10.1088/1748-9326/ab6c70.

Cansler, C. A., V. R. Kane, P. F. Hessburg, J. T. Kane, S. M. A. Jeronimo, J. A. Lutz, N. A. Povak, D. J. Churchill, and A. J. Larson. 2022. "Previous Wildfires and Management Treatments Moderate Subsequent Fire Severity." *Forest Ecology and Management* 504: 119764. https://doi.org/10.1016/j.foreco.2021.119764.

Chiono, L. A., K. L. O'Hara, M. J. De Lasaux, G. A. Nader, and S. L. Stephens. 2012. "Development of Vegetation and Surface Fuels Following Fire Hazard Reduction Treatment." *Forests* 3(3): 700–722. https://doi.org/10.3390/f3030700.

Collins, B. M., J. M. Lydersen, R. G. Everett, and S. L. Stephens. 2018. "How Does Forest Recovery Following Moderate-Severity Fire Influence Effects of Subsequent Wildfire in Mixed-Conifer Forests?" *Fire Ecology* 14(2): 1–9. https://doi.org/10.1186/s42408-018-0004-x.

Collins, B. M., J. D. Miller, A. E. Thode, M. Kelly, J. W. Van Wagtendonk, and S. L. Stephens. 2009. "Interactions among Wildland Fires in a Long-Established Sierra Nevada Natural Fire Area." *Ecosystems* 12(1): 114–128. https://doi.org/10.1007/s10021-008-9211-7.

Collins, L., A. F. Bennett, S. W. J. Leonard, and T. D. Penman. 2019. "Wildfire Refugia in Forests: Severe Fire Weather and Drought Mute the Influence of Topography and Fuel Age." *Global Change Biology* 25(11): 3829–43. https://doi.org/10.1111/gcb.14735.

Coop, J. D., S. A. Parks, C. S. Stevens-Rumann, S. D. Crausbay, P. E. Higuera, K. T. Davis, S. Dobrowski, et al. 2020. "Wildfire-Driven Forest Conversion in Western North American Landscapes." *Bioscience* 70(8): 659–673. https://doi.org/10.1093/biosci/biaa061.

Coop, J. D., S. A. Parks, C. S. Stevens-Rumann, S. M. Ritter, and C. M. Hoffman. 2022. "Extreme Fire Spread Events and Area Burned under Recent and Future Climate in the Western USA." *Global Ecology and Biogeography* 31(10): 1949–59. https://doi.org/10.1111/geb.13496.

Coppoletta, M., K. E. Merriam, and B. M. Collins. 2016. "Post-Fire Vegetation and Fuel Development Influences Fire Severity Patterns in Reburns." *Ecological Applications* 26(3): 686–699. https://doi.org/10.1890/15-0225.

Dennison, P. E., S. C. Brewer, J. D. Arnold, and M. A. Moritz. 2014. "Large Wildfire Trends in the Western United States, 1984-2011." *Geophysical Research Letters* 41(8): 2928–33. https://doi.org/10.1002/2014GL059576.

Eidenshink, J., B. Schwind, K. Brewer, Z.-L. Zhu, B. Quayle, and S. Howard. 2007. "A Project for Monitoring Trends in Burn Severity." *Fire Ecology* 3(1): 3–21.

Greenler, S. M., C. J. Dunn, J. D. Johnston, M. J. Reilly, A. G. Merschel, R. K. Hagmann, and J. D. Bailey. 2023. "Too Hot, Too Cold, or Just Right: Can Wildfire Restore Dry Forests of the Interior Pacific Northwest?" *PLoS One* 18(2): e0281927. https://doi.org/10.1371/journal.pone.0281927.

Hagmann, R. K., P. F. Hessburg, S. J. Prichard, N. A. Povak, P. M. Brown, P. Z. Fulé, R. E. Keane, et al. 2021. "Evidence for Widespread Changes in the Structure, Composition, and Fire Regimes of Western North American Forests." *Ecological Applications* 31(8): e02431. https://doi.org/10.1002/eap.2431.

Harvey, B. J., M. S. Buonanduci, and M. G. Turner. 2023. "Spatial Interactions among Short-Interval Fires Reshape Forest Landscapes." *Global Ecology and Biogeography* 32: 586–602. https://doi.org/10.1111/geb.13634.

Harvey, B. J., D. C. Donato, and M. G. Turner. 2016. "Burn me Twice, Shame on Who? Interactions between Successive Forest Fires across a Temperate Mountain Region." *Ecology* 97(9): 2272–82. https://doi.org/10.1002/ecy.1439.

Hastie, T., and R. Tibshirani. 1987. "Generalized Additive Models: Some Applications." *Journal of the American Statistical Association* 82(398): 371–386. https://doi.org/10.1080/01621459.1987.10478440.

Hessburg, P. F., J. K. Agee, and F. Jerry. 2005. "Dry Forests and Wildland Fires of the Inland Northwest USA: Contrasting the Landscape Ecology of the Pre-Settlement and Modern Eras." *Forest Ecology and Management* 211: 117–139.

Hessburg, P. F., D. J. Churchill, A. J. Larson, R. D. Haugo, C. Miller, T. A. Spies, M. P. North, et al. 2015. "Restoring Fire-Prone Inland Pacific Landscapes: Seven Core Principles." *Landscape Ecology* 30(10): 1805–35. https://doi.org/10.1007/s10980-015-0218-0.

Hijmans, R. J. 2022. "raster: Geographic Data Analysis and Modeling." R Package Version 3.6-14. https://cran.r-project.org/package=raster.

Holden, Z. A., P. Morgan, and A. T. Hudak. 2010. "Burn Severity of Areas Reburned by Wildfires in the Gila National Forest, New Mexico, USA." *Fire Ecology* 6(3): 77–85. https://doi.org/10.4996/fireecology.0603077.

Johnstone, J. F., C. D. Allen, J. F. Franklin, L. E. Frelich, B. J. Harvey, P. E. Higuera, M. C. Mack, et al. 2016. "Changing Disturbance Regimes, Ecological Memory, and Forest Resilience." *Frontiers in Ecology and the Environment* 14(7): 369–378. https://doi.org/10.1002/fee.1311.

Keeley, J. E., M. Baer-Keeley, and C. J. Fotheringham. 2005. "Alien Plant Dynamics Following Fire in Mediterranean-Climate California Shrublands." *Ecological Applications* 15(6): 2109–25. https://doi.org/10.1890/04-1222.

Kerns, B. K., C. Tortorelli, M. A. Day, T. Nietupski, A. M. G. G. Barros, J. B. Kim, and M. A. Krawchuk. 2020. "Invasive Grasses: A New Perfect Storm for Forested Ecosystems?" *Forest Ecology and Management* 463(November 2019): 117985. https://doi.org/10.1016/j.foreco.2020.117985.

Key, C. H., and N. Benson. 2006. "Landscape Assessment: Ground Measure of Severity, the Composite Burn Index; and Remote Sensing of Severity, the Normalized Burn Ratio." https://www.researchgate.net/publication/241687027.

Krawchuk, M. A., and M. A. Moritz. 2011. "Constraints on Global Fire Activity Vary across a Resource Gradient." *Ecology* 92(1): 121–132.

LANDFIRE. 2019a. *Biophysical Setting*. Department of the Interior, Geological Survey, and United States Department of Agriculture. https://landfire.gov/data/citation.

LANDFIRE. 2019b. *Digital Elevation Model*. Department of the Interior, Geological Survey, and United States Department of Agriculture. https://landfire.gov/data/citation.

Larson, A. J., S. M. A. Jeronimo, P. F. Hessburg, J. A. Lutz, N. A. Povak, C. A. Cansler, V. R. Kane, and D. J. Churchill. 2022. "Tamm Review: Ecological Principles to Guide Post-Fire Forest Landscape Management in the Inland Pacific and Northern Rocky Mountain Regions." *Forest Ecology and Management* 504: 119680. https://doi.org/10.1016/j.foreco.2021.119680.

Larson, A. J., R. Travis Belote, C. Alina Cansler, S. A. Parks, and M. S. Dietz. 2013. "Latent Resilience in Ponderosa Pine Forest: Effects of Resumed Frequent Fire." *Ecological Applications* 23(6): 1243–49. https://doi.org/10.1890/13-0066.1.

Lydersen, J. M., B. M. Collins, M. L. Brooks, J. R. Matchett, K. L. Shive, N. A. Povak, V. R. Kane, and D. F. Smith. 2017. "Evidence of Fuels Management and Fire Weather Influencing Fire Severity in an Extreme Fire Event." *Ecological Applications* 27(7): 2013–30. https://doi.org/10.1002/eap.1586.

Lydersen, J. M., M. P. North, and B. M. Collins. 2014. "Severity of an Uncharacteristically Large Wildfire, the Rim Fire, in Forests with Relatively Restored Frequent Fire Regimes." *Forest Ecology and Management* 328: 326–334. https://doi.org/10.1016/j.foreco.2014.06.005.

Makowski, D., M. S. Ben-Shachar, I. Patil, and D. Lüdecke. 2020. "Estimation of Model-Based Predictions, Contrasts and Means." CRAN. https://github.com/easystats/modelbased.

Marra, G., and S. N. Wood. 2011. "Practical Variable Selection for Generalized Additive Models." *Computational Statistics and Data Analysis* 55(7): 2372–87. https://doi.org/10.1016/j.csda.2011.02.004.

McCune, B., and D. Keon. 2002. "Equations for Potential Annual Direct Incident Radiation and Heat Load." *Journal of Vegetation Science* 13(4): 603–6. https://doi.org/10.1111/j.1654-1103.2002.tb02087.x.

Mu, Q., M. Zhao, and S. W. Running. 2014. "MODIS Global Terrestrial Evapotranspiration (ET) Product MOD16A2 Collection 5." University of Montana Numerical Terradynamic Simulation Group.

National Interagency Fire Center. 2022. "WFIGS Interagency Fire Perimeters." https://data-nifc.opendata.arcgis.com/Datasets/Nifc::Wfigs-Interagency-Fire-Perimeters/Explore?Location=-0.000000%2C0.000000%2C1.94.

North, M. P., R. A. York, B. M. Collins, M. D. Hurteau, G. M. Jones, E. E. Knapp, L. Kobziar, et al. 2021. "Pyrosilviculture Needed for Landscape Resilience of Dry Western United States Forests." *Journal of Forestry* 119(5): 520–544. https://doi.org/10.1093/jofore/fvab026.

Olson, D. M., and E. Dinerstein. 2002. "The Global 200: Priority Ecoregions for Global Conservation." *Annals of the Missouri Botanical Garden* 89(2): 199–224.

Parks, S. A. 2014. "Mapping Day-of-Burning with Coarse-Resolution Satellite Fire-Detection Data." *International Journal of Wildland Fire* 23(2): 215–223. https://doi.org/10.1071/WF13138.

Parks, S. A., and J. T. Abatzoglou. 2020. "Warmer and Drier Fire Seasons Contribute to Increases in Area Burned at High Severity in Western US Forests from 1985 to 2017." *Geophysical Research Letters* 47(22): e2020GL089858. https://doi.org/10.1029/2020GL089858.

Parks, S. A., L. M. Holsinger, M. J. Koontz, L. Collins, E. Whitman, M. A. Parisien, R. A. Loehman, et al. 2019. "Giving Ecological Meaning to Satellite-Derived Fire Severity Metrics across North American Forests." *Remote Sensing* 11(14): 1735. https://doi.org/10.3390/rs11141735.

Parks, S. A., L. M. Holsinger, C. Miller, and C. R. Nelson. 2015. "Wildland Fire as a Self-Regulating Mechanism: The Role of Previous Burns and Weather in Limiting Fire Progression." *Ecological Applications* 25(6): 1478–92. https://doi.org/10.1890/14-1430.1.

Parks, S. A., L. M. Holsinger, M. H. Panunto, W. M. Jolly, S. Z. Dobrowski, and G. K. Dillon. 2018. "High-Severity Fire: Evaluating Its Key Drivers and Mapping Its Probability across Western US Forests." *Environmental Research Letters* 13(4): 044037. https://doi.org/10.1088/1748-9326/aab791.

Parks, S. A., C. Miller, C. R. Nelson, and Z. A. Holden. 2014. "Previous Fires Moderate Burn Severity of Subsequent Wildland Fires in Two Large Western US Wilderness Areas." *Ecosystems* 17(1): 29–42. https://doi.org/10.1007/s10021-013-9704-x.

Parks, S. A., M. A. Parisien, C. Miller, L. M. Holsinger, and L. S. Baggett. 2018. "Fine-Scale Spatial Climate Variation and Drought Mediate the Likelihood of Reburning." *Ecological Applications* 28(2): 573–586. https://doi.org/10.1002/eap.1671.

Pausas, J. G., and J. E. Keeley. 2017. "Epicormic Resprouting in Fire-Prone Ecosystems." *Trends in Plant Science* 22(12): 1008–15. https://doi.org/10.1016/j.tplants.2017.08.010.

Prichard, S. J., C. S. Stevens-Rumann, and P. F. Hessburg. 2017. "Tamm Review: Shifting Global Fire Regimes: Lessons from Reburns and Research Needs." *Forest Ecology and Management* 396: 217–233. https://doi.org/10.1016/j.foreco.2017.03.035.

PRISM Climate Group. 2022. *PRISM Climate Group*. Corvallis, OR: Oregon State University. https://prism.oregonstate.edu/.

R Core Team. 2022. *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing. https://www.r-project.org/.

Reilly, M. J., C. J. Dunn, G. W. Meigs, T. A. Spies, R. E. Kennedy, J. D. Bailey, and K. Briggs. 2017. "Contemporary Patterns of

Fire Extent and Severity in Forests of the Pacific Northwest, USA (1985-2010).” *Ecosphere* 8(3): e01695. https://doi.org/10.1002/ecs2.1695.

Rodman, K. C., K. T. Davis, S. A. Parks, T. B. Chapman, J. D. Coop, J. M. Iniguez, J. P. Roccaforte, et al. 2023. “Refuge-Yeah or Refuge-Nah? Predicting Locations of Forest Resistance and Recruitment in a Fiery World.” *Global Change Biology* 29: 7029–50. https://doi.org/10.1111/gcb.16939.

Saberi, S. J., and B. J. Harvey. 2023. “What Is the Color When Black Is Burned? Quantifying (Re)Burn Severity Using Field and Satellite Indices.” *Fire Ecology* 19: 1–17. https://doi.org/10.1186/s42408-023-00178-3.

Steel, Z. L., H. D. Safford, and J. H. Viers. 2015. “The Fire Frequency-Severity Relationship and the Legacy of Fire Suppression in California Forests.” *Ecosphere* 6(1): 1–23. https://doi.org/10.1890/ES14-00224.1.

Stevens, J. T., C. M. Haffey, J. D. Coop, P. J. Fornwalt, L. Yocom, C. D. Allen, A. Bradley, et al. 2021. “Tamm Review: Postfire Landscape Management in Frequent-Fire Conifer Forests of the SouthWestern United States.” *Forest Ecology and Management* 502(June): 119678. https://doi.org/10.1016/j.foreco.2021.119678.

Stevens-Rumann, C., and P. Morgan. 2016. “Repeated Wildfres Alter Forest Recovery of Mixed-Conifer Ecosystems.” *Ecological Applications* 26(6): 1842–53. https://doi.org/10.1890/15-1521.1.

Taylor, A. H., L. B. Harris, and S. A. Drury. 2021. “Drivers of Fire Severity Shift as Landscapes Transition to an Active Fire Regime, Klamath Mountains, USA.” *Ecosphere* 12(9): e03734. https://doi.org/10.1002/ECS2.3734.

Taylor, A. H., L. B. Harris, and C. N. Skinner. 2022. “Severity Patterns of the 2021 Dixie Fire Exemplify the Need to Increase Low-Severity Fire Treatments in California’s Forests.” *Environmental Research Letters* 17(7): 071002. https://doi.org/10.1088/1748-9326/ac7735.

Taylor, A. H., V. Trouet, C. N. Skinner, and S. Stephens. 2016. “Socioecological Transitions Trigger Fire Regime Shifts and Modulate Fire-Climate Interactions in the Sierra Nevada, USA, 1600-2015 CE.” *Proceedings of the National Academy of Sciences of the United States of America* 113(48): 13684–89. https://doi.org/10.1073/pnas.1609775113.

Tortorelli, C., J. Kim, N. M. Vaillant, K. Riley, A. Dye, K. C. Vogler, R. Lemons, M. Day, M. Krawchuk, and B. K. Kerns. 2023. “Feeding the Fire: Annual Grass Invasion Facilitates Modeled Fire Spread across Inland Northwest Forest-Mosaic Landscapes.” *Ecosphere* 14(2): e4413. https://doi.org/10.1002/ecs2.4413.

Tortorelli, C., and D. Young. 2024. “cmtortorelli/reburn-project: Reburn Project 1.0 (v1.0).” Zenodo. https://doi.org/10.5281/zenodo.11490965.

Turner, M. G., K. H. Braziunas, W. D. Hansen, and B. J. Harvey. 2019. “Short-Interval Severe Fire Erodes the Resilience of Subalpine Lodgepole Pine Forests.” *Proceedings of the National Academy of Sciences of the United States of America* 166(23): 11319–28. https://doi.org/10.1073/pnas.1902841116.

USDA Agricultural Research Service. 2022. “Rangeland Analysis Platform.”

Vaillant, N. M., E. Noonan-Wright, S. Dailey, C. Ewell, and A. Reiner. 2013. “Effectiveness and Longevity of Fuel Treatments in Coniferous Forests across California.” http://digitalcommons.unl.edu/jfspresearchhttp://digitalcommons.unl.edu/jfspresearch/57.

Williams, J. N., H. D. Safford, N. Enstice, Z. L. Steel, and A. K. Paulson. 2023. “High-Severity Burned Area and Proportion Exceed Historic Conditions in Sierra Nevada, California, and Adjacent Ranges.” *Ecosphere* 14(1): e4397. https://doi.org/10.1002/ecs2.4397.

Wood, S. N. 2017. *Generalized Additive Models: An Introduction with R*, 2nd ed. New York, NY: Chapman & Hall/CRC.

Yocom, L. L., J. Jenness, P. Z. Fulé, and A. E. Thode. 2022. “Fire Severity in Reburns Depends on Vegetation Type in Arizona and New Mexico, U.S.A.” *Forests* 13(11): 1957. https://doi.org/10.3390/f13111957.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Tortorelli, Claire M., Andrew M. Latimer, and Derek J. N. Young. 2024. “Moderating Effects of Past Wildfire on Reburn Severity Depend on Climate and Initial Severity in Western US Forests.” *Ecological Applications* e3023. https://doi.org/10.1002/eap.3023