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System-level feedbacks of active fire regimes in large landscapes

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Abstract

Background Climate is a main driver of fire regimes, but recurrent fires provide stabilizing feedbacks at several spatial scales that can limit fire spread and severity—potentially contributing to a form of self-regulation. Evaluating the strength of these feedbacks in wildland systems is difficult given the spatial and temporal scales of observation required. Here, we used the REBURN model to directly examine the relative strengths of top-down and bottom-up drivers of fire over a 3000-year simulation period, within a 275,000-ha conifer-dominated landscape in north central Washington State, USA.

Results We found strong support for top-down and bottom-up spatial and temporal controls on fire patterns. Fire weather was a main driver of large fire occurrence, but area burned was moderated by ignition frequencies and by areas of limited fuels and fuel contagion (i.e., fire fences). Landscapes comprised of >40% area in fire fences rarely experienced large fire years. When large fires did occur during the simulation period, a recovery time of 100–300 years or more was generally required to recover pre-fire vegetation patterns.

Conclusions Simulations showed that interactions between fire weather, fuel contagion, topography, and ignitions manifest variability in fire size and severity patch size distributions. Burned and recovering vegetation mosaics provided functional stabilizing feedbacks, a kind of *meta*stability, which limited future fire size and severity, even under extreme weather conditions. REBURN can be applied to new geographic and physiographic landscapes to simulate these interactions and to represent natural and culturally influenced fire regimes in historical, current, or future climatic settings.

Keywords Stabilizing feedbacks, The REBURN model, Regional landscape resilience, Fire severity, Patch size distributions, Wildfire spatial controls

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Resumen

Antecedentes El clima es el principal determinante de los regímenes de fuegos, aunque fuegos recurrentes actúan como estabilizadores de esa retroalimentación a diferentes escalas espaciales: esto puede limitar su propagación y severidad, contribuyendo así a una forma de autoperpetuación. Evaluar la fortaleza de esas retroalimentaciones en ecosistemas vegetales naturales es difícil dadas las escalas espaciales y temporales de observación requeridas. En este trabajo, usamos el modelo REBURN para examinar directamente las fortalezas relativas de los determinantes de los fuegos de arriba hacia abajo, *(top-down*) y de abajo hacia arriba (*bottom-up*) por un período simulado de 3000 años, dentro de un paisaje de 275000 ha de boques dominados por coníferas en el centro norte del estado de Washington, EEUU.

Resultados Encontramos muy fuertes evidencias de controles *top-down* y *bottom-up* para los patrones espaciales y temporales de incendios. El estado del tiempo meteorológico durante el desarrollo de los fuegos fue el factor determinante en la ocurrencia de grandes incendios, aunque el área quemada fue moderada por la frecuencia de las igniciones y por áreas con limitaciones en combustibles y barreras contra el fuego. Los paisajes que estaban ubicados en áreas con >40% de barreras contra fuegos raramente experimentaron grandes incendios. Cuando ocurrieron grandes incendios se requirió de un período de entre 100 y 300 años en recuperar los patrones de vegetación pre-fuego.

Conclusiones Las simulaciones mostraron que las interacciones entre el tiempo meteorológico durante los incendios, las barreras contra fuegos, la topografía y las igniciones manifiestan na serie de variabilidades en el tamaño de los incendios y la severidad y distribución de tamaños en los parches quemados. Similarmente, las simulaciones revelaron que los mosaicos quemados y en recuperación proveyeron de retroalimentaciones que confirieron de estabilidad, un tipo de meta- estabilidad, lo que limitó el tamaño y severidad de futuros fuegos, aún en casos condiciones meteorológicas extremas. El programa REBURN puede ser aplicado a nuevos paisajes geográficos y fisiográficos para simular esas interacciones y para representar contextos climáticos pasados, actuales o previstos para el futuro.

Introduction

In recent decades, recurring large and severe wildfire seasons have become emblematic of western North American (wNA) forests and rangelands (Westerling et al. 2006; Dennison et al. 2014). With trends toward increasing area burned in large and severe wildfires (Parks and Abatzoglou 2020), questions remain regarding how to foster landscape resilience under a changing climate. Will large wildfires remain the dominant change agent? Can restoration of characteristic fire regimes (Hessburg et al. 2021; Prichard et al. 2021) reinstate climate- and fire-adapted landscapes? Can fuel reduction and maintenance work (Stephens et al. 2020; Prichard et al. 2021) be scaled to meet this challenge? Will ongoing wildfires provide the essential treatments for adaptation?

Theoretical studies of fire-vegetation and fire-fire interactions suggest that wildland fire events can be self-limiting over space and time (Malamud et al. 1998; Reed and McKelvey 2002; Peterson 2002). For example, Moritz et al. (2011) demonstrated that patterns and patch size distributions of prior fires and post-fire succession trajectories likely constrained future fire event sizes. From their modeling, they showed that extreme exogenous weather and climatic events primarily controlled the largest fire events, a mix of exogenous and endogenous factors controlled the sizes of the more numerous medium-sized events, and localized endogenous factors constrained the sizes of the most numerous small events. According to their results, the functional role of smaller fires was to break up large contagious vegetation and fuel patches with recently burned or recovering conditions. The resulting patchwork then provided an effective, time-lagged negative feedback to the frequency and size of large and severe fires (Peterson 2002; Moritz et al. 2011).

Strong feedbacks within dynamic landscapes can lead to disturbance mediated system self-regulation where pattern-process interactions support characteristic system-level properties that generally deviate within a restricted set of conditions (i.e., a metastability, sensu Wu and Loucks 1995), except under rare circumstances (Peterson 2002; Moritz et al. 2005; Parks et al. 2015a). This self-regulation is characterized by the ability for systems to effectively constrain fire occurrence (Parks et al. 2015a), severity (Cansler et al. 2022), and spread (Collins et al. 2009). Over long time periods, these limiting properties must be approximately balanced to maintain characteristic vegetation patterns. For example, strong limits on fire occurrence and recurrence may lessen the capacity of a system to constrain fire severity (Parks et al. 2015b). While the interplay among these factors is poorly studied over long time frames, the potential consequences of their imbalance could have important implications for system-level dynamics for decades to centuries (Haugo et al. 2019).

Empirical studies of recent historical landscapes and their fire regimes also provide evidence of these negative feedbacks. Prior to dominant Euro-American settler colonization in the western US (Hessburg et al. 1999, 2000a, b), forest and non-forest vegetation types and physiognomic conditions were largely patterned through disturbance interactions with varied biophysical gradients and topographic settings (Hessburg et al. 1999, 2000a, b, 2016, 2019). Fires both responded to these patterns as well as created additional patterning through repeated and overlapping burns. These *reburns* created regional patchworks of decoupled surface and canopy fuels that limited contagion of areas with high crown fire potential (Collins et al. 2007, 2009; Hessburg et al. 2016, 2019; Holden et al. 2010; Moritz et al. 2011). Here, we refer to reburns as overlapping areas that burned at least once after an initial fire.

Fire-vegetation and fire-fire dynamics are highly responsive to changes in climate and environmental conditions. This is reflected in recent surge in research activity in the climate change and wildfire sciences. However, critical to our understanding of these dynamics is our ability to identify climate, weather, and vegetation conditions that stabilize or destabilize landscapes (Wu and Loucks 1995). Also critical is the determination of whether spatial (burned and recovering patchworks) and temporal (time-since-fire) controls have been substantially altered, and where landscape tipping points might be present (Falk et al. 2022).

The objective of this study was to use the landscape simulation model introduced by Prichard et al. (2023) to evaluate the effects of wildfires and patterns of reburning to characterize and quantify key aspects of the active fire regime of a large landscape. We developed a spatial simulation model to capture long-term climate-fire-vegetation feedbacks in a large, forested area of the inland Pacific Northwest. Our model (hereafter, the REBURN model) was inspired by Davis et al. (2010) who evaluated the consequences of fire suppression in a case study landscape of the central Sierra Nevada Mountains. The authors used iterative FARSITE simulations with state-transition models to represent fuel succession and wildfire dynamics. Iterative modeling of landscape stabilizing fire feedbacks was also done by Peterson (2002), who used a numerical simulation model of frequent fire systems to explore how fire patterns are influenced by prior disturbance and regrowth history (i.e., ecological memories). Peterson (2002) used a modified Drossel and Schwabl (1992) forest fire cellular automata model with an additional parameter to vary the probability of fire spread into adjacent cells based on their time since last fire. The strength of the ecological memory in their model was determined by the rate at which the probability of spread into previously burned cells increased as barriers to fire spread faded. Simulations showed that the degree to which ecological memory shaped future ecosystem dynamics depended upon the rate of vegetation recovery, and disturbance frequency. Significant disruptions in one or more of these variables led to abrupt, non-linear state shifts, particularly in large spaces where ecological memory was especially weakened.

Concepts of ecological memory and landscape contagion are highly relevant to wNA wildfires, but few models facilitate evaluation of these interactions at spatial and temporal scales large enough to capture the dynamics associated with regional fire regimes (e.g., 10^5 to 10^6 ha). Such scaling is needed to determine the influence of broad landscape fuel, physiognomic, and forest successional patterns on system-level properties. Consequently, we developed a geospatial vegetation and fuel succession model (REBURN, Prichard et al. 2023) that integrates a landscape fire simulation model (FSPro, Calkin et al. 2011).

Here, we present the results of a 3000-year simulation of vegetation and wildfire dynamics across the footprint of the 2006 Tripod Complex fire that burned in eastern Washington (Fig. 1). The Tripod study area is representative of a much larger region which, prior to 2006, had experienced a long absence of fire (Prichard et al. 2010; Prichard and Kennedy 2014; Hessburg et al. 2005). We were motivated to understand what dynamics might have existed if an active fire regime had been allowed prior to the 2006 fire. We explored the importance of fire-vegetation and fire-fire (hereafter, *reburns*) interactions in driving long-term system-level dynamics under an active fire regime without fire suppression. Our evaluation of these dynamics was guided by three key questions:

(1) How do patterns and amounts of forest structure and fuels vary across time and space under an active fire regime?
(2) What was the frequency and variability of large fire years?
(3) What weather, forest structure, and fuel contagion conditions were generally associated with large fire years, and how did surface and canopy fuel contagion, fire weather, and topography interact to drive observed variability of fire size and severity?

Methods

Study area

Our study area resides in the Okanogan Highlands of north central Washington State in an area that fully encompasses the 2006 Tripod Complex fire (Fig. 1). Knowing that many wildfires originate from outside of a landscape of interest, we established a full rectangular bounding extent by adding a 7.5-km buffer around the Tripod perimeter. This allowed for ignitions to occur both within and adjacent to the Tripod landscape and

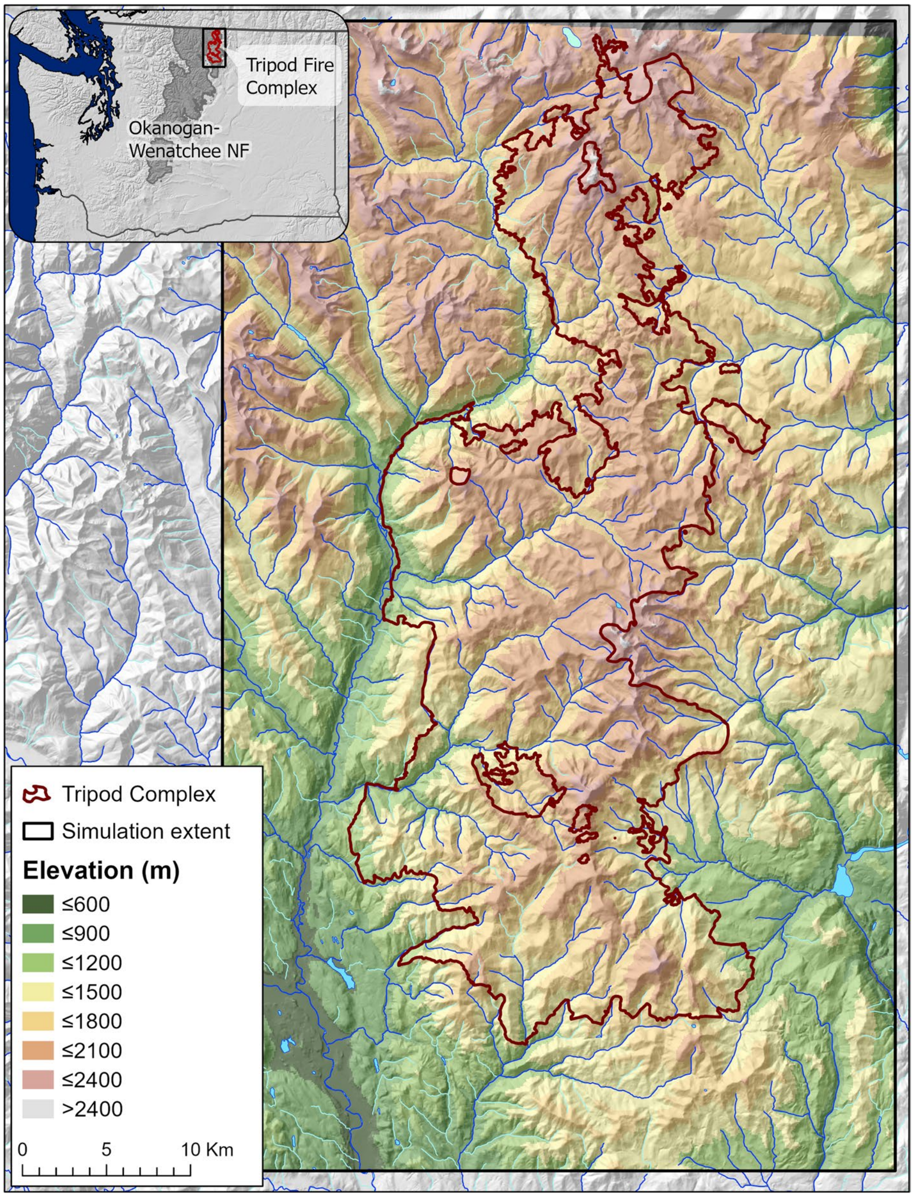

Fig. 1 Study area map depicting the 274,302-ha modeled study area surrounding the 70,894-ha 2006 Tripod Complex fire (red outline) in north central Washington State, USA

fairly represent the potential fire migration, fire-vegetation, and fire-fire dynamics of the entire area (Fig. 2). The resulting 274,302-ha (677,815-ac) landscape contained forest types that ranged from high elevation, cold-dry (CDC) and cold-moist (CMC) mixed conifer [lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*)] forests, moist-mixed conifer forests (MMC) of western larch (*Larix occidentalis*), Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), and lodgepole pine in the middle elevations, and ponderosa pine (*Pinus ponderosa*) and pine mixed with Douglas-fir dry-mixed conifer forests (DMC) at the lowest elevations (Fig. 2A). Climate is characterized by cold, snowy winters and dry summers, with only 13.2% of the total annual precipitation falling between July and September. Total mean annual precipitation ranges from 318 to 1677 mm, with most precipitation falling as snow between October and March. Average daily maximum temperatures range from −7 to 0° C in January, and 14 to 30° C in August (PRISM, *Norm81m*, 1981–2010, https://prism.oregonstate.edu/).

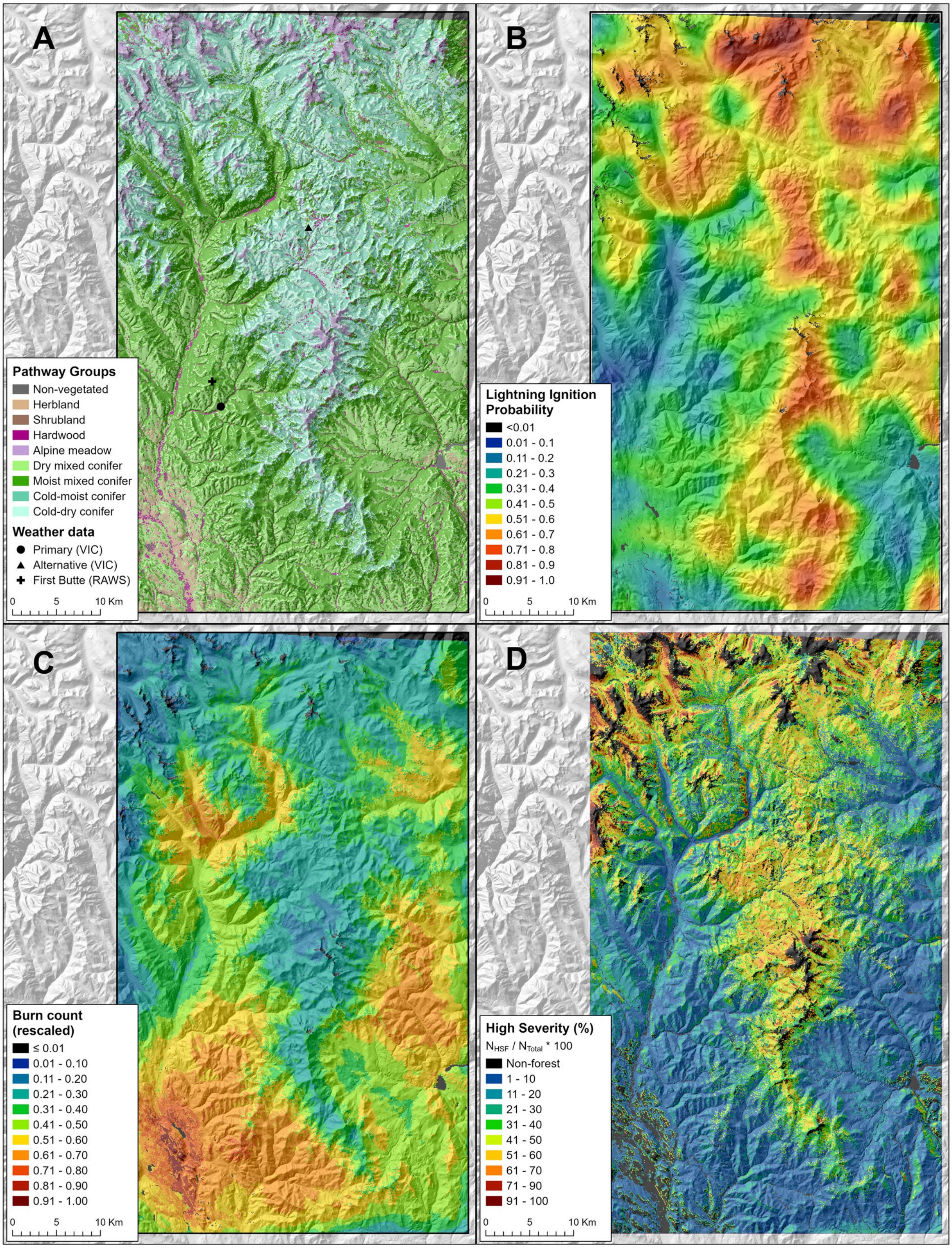

Fig. 2 Distribution of conditions across the Tripod study area. **A** Pathway groups, which were each assigned a different state and transition model based on their biophysical setting, **B** lightning ignition probability, **C** cell-level wildfire burn counts (rescaled relative to the total count) for the 3000-year simulation period, and **D** percentage of high-severity fire burns for each cell. The non-forest label in **D** refers to the 5 non-forest classes in **A**. The dark gray sliver in the northwest portion of the study area is Canada, which was excluded from the model runs

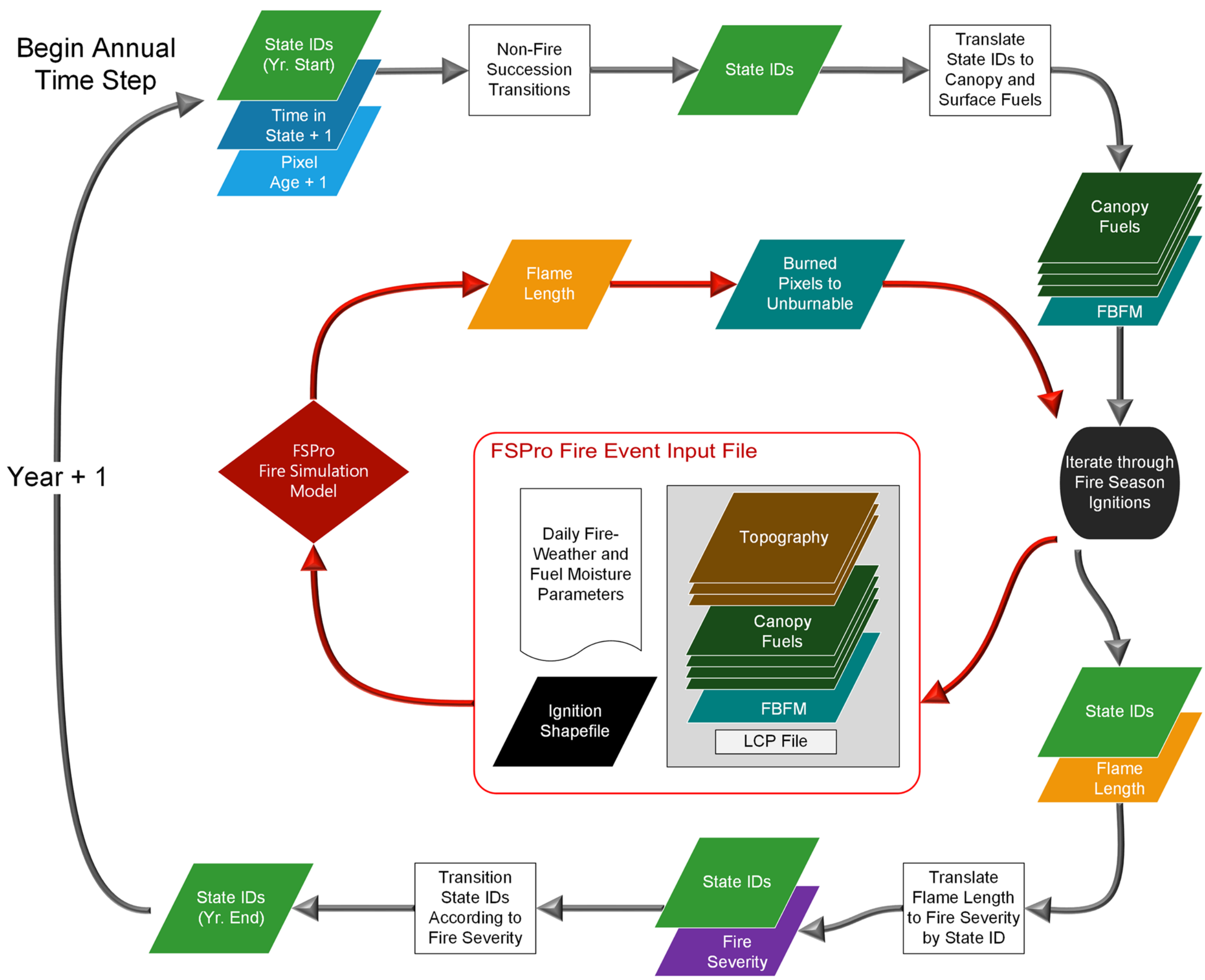

Fig. 3 REBURN workflow diagram. At "Begin annual time step," state and transition models (STMs) grow canopy and surface fuels by 1 year (outer workflow). States within STMs are represented by a *State ID*, which is translated to canopy and surface fuel inputs. All ignitions in a given fire year are modeled with FSPro using daily fire weather and a landscape (LCP file) including terrain, canopy fuel, and surface fuel inputs (*inner workflow diagram*). Burned cells are then update by fire severity (outer workflow) and assigned a new State ID

Overview of the modeling framework

We designed a geospatial modeling framework (REBURN) to evaluate large landscape-level fire-vegetation dynamics over multi-millennial simulated time frames (Fig. 3). Because temperate forests are long lived and have complex landscape dynamics with fires of varying severity, we evaluated dynamics over a period of 3000 years under an unregulated fire regime. REBURN employs an integrated GIS workflow that uses fire simulation modeling to determine annual fire spread and severity from known ignition sources (in this instance, lightning), and customized state-transition (STM) models for each vegetation type (PWGs, see below) to grow vegetation, accumulate fuels, and transition burned cells to new states based on fire severity and productivity. Fire is simulated for each successful ignition in FSPro, and vegetation and fuel succession conditions are updated in annual time steps.

The model iteratively simulates the spread of individual fires using fire ignition probability maps, daily weather inputs, and surface and canopy fuel rasters. STMs (see Prichard et al. 2023 for complete descriptions) represent the full logic of how surface and canopy fuel and forest successional conditions transition from state to state, and the timing of these transitions, for each of several forest types. Forest types are differentiated by their productivity setting (hereafter, forest pathway groups, or PWGs). State transitions in this instance of REBURN are catalyzed by wildfire disturbances, but they can also be initiated by various management mitigation treatments or other disturbance agents that are not yet represented in the model.

REBURN represents the landscape in discrete vegetation states based on their environmental setting (elevation, slope, and aspect), time since fire, and past fire severity. Every 90-m grid cell exists in a burnable or recovering state, or it exists as continuously non-burnable rock, bare ground, water, snow, or ice. Each cell's fuel state is linked to a fire behavior fuel model (FBFM, Scott and Burgan 2005), which represents its surface fuel conditions. Fire severity is determined by the energy released from the fuelbed (where the energy release component (ERC) value is sufficient to catalyze a fire), the resulting flame length, and the canopy fuel conditions associated with that cell. Canopy fuel conditions are represented by the cell's vegetation canopy cover, canopy height, canopy base height, and canopy bulk density. In annual time steps, states representing each cell either stay within state or transition to an earlier or later successional state, depending on the occurrence of fire in that cell and its severity. REBURN was calibrated to approximate pre-industrial fire and vegetation envelopes developed from the independent Interior Columbia River Basin (ICRB) mid-scale data set (Hessburg et al. 1999, 2000a, b). A full model description and results of calibration are presented in Prichard et al. (2023).

The REBURN model was scripted in Python using ArcGIS modules on a desktop computer with 16 GB of RAM, and process time for each 3000-year run took approximately 2.5 weeks.

Vegetation pathway groups (PWGs)

The LANDFIRE biophysical settings (BpS, https://landfire.gov/bps.php) raster (Fig. 2A) was used to allocate PWGs across the study area and to make state-transition model assignments by major vegetation type. These data corresponded with broad vegetation types that were likely present prior to Euro-American colonization given the biogeoclimatic conditions and characteristic disturbance regime (Rollins 2009).

We used the BpS *group level* attribute to assign each 90-m cell to one of water, snow/ice, rock, barren, grassland, shrubland, hardwood/riparian, alpine meadow, dry- or moist-mixed conifer forest, and dry or moist cold conifer forest conditions. The four conifer forest BpS classes were differentiated to dry-mixed (DMC), moist-mixed (MMC), cold-dry (CDC), or cold-moist (CMC) conifer forest conditions based on topographic position, aspect, and elevation (Fig. 2A). Mixed conifer cells were assigned to DMC below 900 m and MMC above 1525 m, regardless of topographic position or aspect (Fig. 1). Above 900 m, MMC and CMC cells located on a ridge top or south aspect were assigned to the DMC or CDC PWG respectively. Conversely, DMC and CDC cells occurring in a valley bottom setting or on north aspects were assigned to the MMC or CMC PWG, respectively (Fig. 2A). Cells residing in environmental settings that were not forest capable did not have a defined STM and were assigned to single state pathways that reverted to its non-forest type in the year after a fire. Cell membership within a PWG was constant across the simulation period because in this initial effort, we were not simulating climatic driven shifts in environmental site potential. This is planned in future work.

State-transition models (STMs)

STMs metered vegetation succession, fire-vegetation dynamics, and state transitions for the four conifer PWG. Prichard et al. (2023) document the STMs in greater detail, but we include basic information here and in supplementary material to provide sufficient context.

Four forest PWG STMs were developed to define surface fuel and forest successional transitions over time. States within the STMs were assigned successional time steps, a surface fire behavior fuel model (FBFM, Anderson 1982; Scott and Burgan 2005), canopy cover (CC, %), canopy height (CH, m), canopy base height (CBH, m), and canopy bulk density (CBD, $kg \cdot m^{-3}$) (Tables S1-S3). Based on these data, each state in the STM was also assigned an O'Hara et al. (1996) forest structural class for subsequent direct comparisons of the simulated conditions and empirically derived data sets (see Prichard et al. 2023). FBFMs were categorical fuel conditions, which were consistent throughout a 90-m cell. Canopy fuel conditions were represented by continuous values of each parameter, which were incrementally "grown" state to state, each year, over the course of a state's development, using a linear ramp function.

Fire spread model

Fire behavior was modeled within FSPro (Calkin et al. 2011), which simulates fire spread, fireline intensity, and flame length based on input ignition points, daily weather streams, fuel moisture data, and a landscape (LCP) file that specifies topography, canopy fuels and surface fuels for each cell. FSPro is used in decision support of actual wildfire events as a probabilistic model to inform decision making based on a range of weather scenarios (Finney et al. 2011). For this study, we used FSPro to model single iteration fire events to simulate fire spread based on landscape fuel conditions, ignition locations, and known rather than probabilistic weather streams.

Input ignition and weather data

Prior to the start of each fire season (fire season determination methods detailed in Prichard et al. (2023), the number of ignitions was drawn from a probability density function, and the spatial ignition locations were drawn from a lightning ignition probability surface (Fig. 2B) for each fire (methods are detailed in Prichard et al. 2023). A fire was removed from the annual count if the ignition landed on a non-burnable fuel model within a burnable PWG. Doing so allowed the model to respond to spatial patterns of non-burnable *fences* and burnable *corridors* (sensu Moritz et al. 2011) to fire flow over the simulation timeline. The number of annual ignitions was randomly drawn from a distribution of fire starts derived from the *Region 6 Fire History Wildfire Points of Origin* dataset (USDA Forest Service 2014). The lightning ignition probability surface was developed from historical lightning strike point data (Fig. 2B, National Lightning Detection Network (NLDN) 1990–2010, Cummins and Murphy 2009) within a specified fire season bounded by noted fire occurrence within the Region 6 fire dataset (March 31 through October 26).

Required weather inputs to FSPro included a time series of daily ERC (Energy Release Component) values, wind speed and direction values, and fuel moistures for each ignition. Daily fuel moisture inputs included 1-, 10-, 100-h time lag dead fuel moistures, live herbaceous and live woody fuel moistures, a specified burn period (minutes), and spotting probability. To derive these data for the 3000-year simulations, we used historical daily weather data from the VIC (Variable Infiltration Capacity[1]) model (Livneh et al. 2013).

Importantly, the model was built using a baseline climate scenario, which randomly drew weather years from a 67-year time series (see below). This was intentionally done to remove long-term climate trends resulting from mid- to long-term climate variability (e.g., El Nino, Pacific Decadal Oscillations, climate change). Our approach allowed for an assessment of system dynamics under relatively stationary climate conditions where long-term vegetation, fuels, and disturbance dynamics unfolded without assuming and modeling specific temporal trends in climate variables over the 3000-year simulation period. Most important, this also provided a benchmark for comparisons with future runs where climate change is incorporated to identify how dynamics vary under variable climatic futures.

VIC weather streams were derived from over 20,000 NOAA Cooperative Observer stations at a spatial resolution of 1/16th degrees latitude/longitude. Data included 3-h time steps for precipitation, temperature, relative humidity, solar radiation, and wind speed for the years 1915–2011. VIC data were selected because they spanned the temporal record of our wildfire ignition database, covered a sufficiently broad geographic extent, and were spatially gridded. We selected a VIC grid point near the First Butte RAWS (Remote Automated Weather Station) station that was within the lower elevation dry- and moist-mixed forest zone. Additionally, we selected a VIC grid point within the high-elevation cold forest zone to provide a span of weather data representative of the elevational gradient of the study area (Fig. 2A).

From these data, we developed daily ERC values for the years 1940–2006 using custom R scripts following the methods of Deeming et al. (1977) and Cohen and Deeming (1985). ERC bins were developed, per the requirements of FSPro, and mean fuel moistures were attributed to each bin using data derived from FireFamily Plus over the 67-year period. Seasonal look up tables were developed to allow for temporal variation in the percentile fuel moistures and burn period lengths across a year. Wind direction and speed were derived from the First Butte RAWS (Remote Automated Weather Station) station from 1998–2015 and included winds recorded between 10:00 AM and 8:00 PM from July 1 to September 30. A wind rose was created from these data, which we used to draw daily wind speed and direction combinations.

Following model calibration (Prichard et al. 2023), we developed an annual weather index from these weather data for each of the 67 weather years based on the median area burned for each year, over the 3000-simulation period. This index ranked weather years in terms of their fire activity representing a fire-centric composite variable to compare severity of fire weather years. This metric was then used in subsequent statistical modeling (see below).

Model workflow and outputs

At the start of each simulation, surface and canopy fuel values were assigned based on each cell's PWG state membership and time in state. For each successive year, unburned cells advanced 1 year in their respective STMs and either stayed within the current state or transitioned to a new state, depending on the time in state (Fig. 3). Surface fuel conditions changed when a cell transitioned to a new state, and canopy fuels changed annually according to a linear ramp function between states. Within each fire season, burned cells were set to a non-burnable surface fuel model (NB9) and were not available to reburn for the remainder of the fire season. Following a fire season, a short-term elimination of surface fuels (NB9) was assigned based on PWG (herbland = 0 y; shrubland, hardwood, alpine meadow = 5 y; DMC = 5 y, MMC = 5 y; CMC = 5 y; and CDC = 10 y). This conservative post-fire refractory period was based on the length of time a past fire is expected to remain a barrier to fire within the study area considering the findings of Prichard et al. (2010), Prichard and Kennedy (2014), and Stevens-Rumann et al. (2016). State transitions following each fire season were based on lookup tables that converted flame lengths to severity class (unburned/very low, low, moderate, and high), which were unique to each state's vegetation and fuel conditions.

[1] ftp://livnehpublicstorage.colorado.edu/public/Livneh.2013.CONUS.Dataset/Derived.Subdaily.Outputs.asc.v.1.2.1915.2011.bz2/

Severity classes were then used to initiate state transitions (Prichard et al. 2023). After all, cells were updated to their new states and time in state, the process began again for the next fire year (Fig. 3). Each state was assigned one of eight structural classes (O'Hara et al. 1996) to depict the stage of structural development along a continuum from post-fire bare ground to old forest conditions. This attribution was a post hoc classification used for subsequent analyses and interpretation of results. Importantly, the structural classification scheme did not influence the definition of states, transitions, or the fire spread modeling.

Statistical analyses

To evaluate model behavior and system-level dynamics of fire-fire interactions, we conducted several analyses on the forest structure, fuels, and wildfire size and severity outputs from the REBURN model. Four questions guided our analyses:

Question 1. How do patterns and amounts of forest structure and fuels vary across time and space under an active fire regime?

We used wavelet analysis to identify temporal patterns in annually resolved burned area across the study domain across the 3000-year simulation. By means of wavelet analysis, we could directly evaluate potential multi-scaled fire frequency patterns and (non)stationarity in annual area burned patterns across the simulation period. Given that weather years were randomly drawn and applied to the extant landscape at the time, we did not expect to see evidence of broad fluctuations in active fire regime properties due to the lack of strong temporal trends in the climate. However, we did expect that shorter-term patterns in fire regime properties would result from post-fire refractory periods and subsequent fuel accumulation following large fire years. Wavelet analysis is particularly adept at identifying short- to long-term trends in time series as well non-stationarity in those trends. We conducted wavelet analysis using the *dplR* package (Bunn et al. 2022) in the R v4.0.4 statistical environment (R Core Team 2021). The Morlet wavelet transformation was selected for analysis as it accommodates nonstationary power at multiple frequencies and allows for the flexibility to identify such behavior (Torrence and Compo 1998). Mean return intervals for each structural class and for area burned were determined by the wavelet period corresponding to the maximum power spectrum.

Question 2. What was the frequency and variability of large fire years?

Principal components analysis of extreme fire years (> 150,000 ha) Eight simulation years supported annual area burned >150,000 ha, an area more than twice as large as the Tripod Complex fire of 2006. This set of fire years represented the 99.7th percentile annual area burned across the 3000-year simulation period. These were used to evaluate the number of years required for the landscape to return to structurally similar pre-fire conditions. For each fire year, we quantified the percentage of the landscape in each of three simplified fuel classes (see below) in the year prior to the fire. We also computed the class-level interspersion-juxtaposition index (IJI) of the three fuel classes as a measure of their spatial patterning in any given year. IJI values range from 0 (classes only adjacent to a single other class) to 100 (classes equally adjacent to other classes). The IJI measure was chosen as it was poorly correlated with the percentage area (percent land, PL) in the fuel classes ($r < 0.61$), and it performed well compared to using a larger set of landscape metrics.

We used k-nearest neighbor analysis ($k = 1$) to identify the post-fire landscape condition most like the pre-fire conditions for each of the eight largest fires. The number of years between pre-fire and post-fire nearest neighbor conditions indicated the recovery period. Principal components analysis (PCA) was used to visualize the extreme fire-driven changes to structural conditions compared to all other years (*prcomp*, R v4.0.4). Data for the PCA included the percentage of the landscape in each of the three fuel classes and the IJI for each class. Data were square root transformed prior to the PCA.

Question 3. What weather, forest structure, and fuel contagion conditions were generally associated with large fire years, and how did surface and canopy fuel contagion, fire weather, and topography interact to drive observed variability of fire size and severity?

Superposed epoch analysis (extreme fire years > 150,000 ha) To assess potential landscape-level surface and canopy fuel contagion as a contributor to large fire years, we characterized the amount and contagion of fuels for each simulation year (Tables S1-S3). We assigned each *state ID* to one of three simplified fuel classes: (1) *None*, non-burnable or subject to very low flame lengths and spread rates, (2) *Fire Flow Enabler* (FFE), surface fuel loads conducive to low flame lengths and high rates of spread, and (3) *Crown Fire Potential* (CFP), surface and canopy fuels vulnerable to crown fire initiation and spread. We then used superposed epoch analysis (SEA, Grissino-Mayer 1995) to identify significant relationships between the temporal patterns of fuel classes and extreme fire years (>150,000 ha burned). SEA was conducted in the *dplR* package in R.

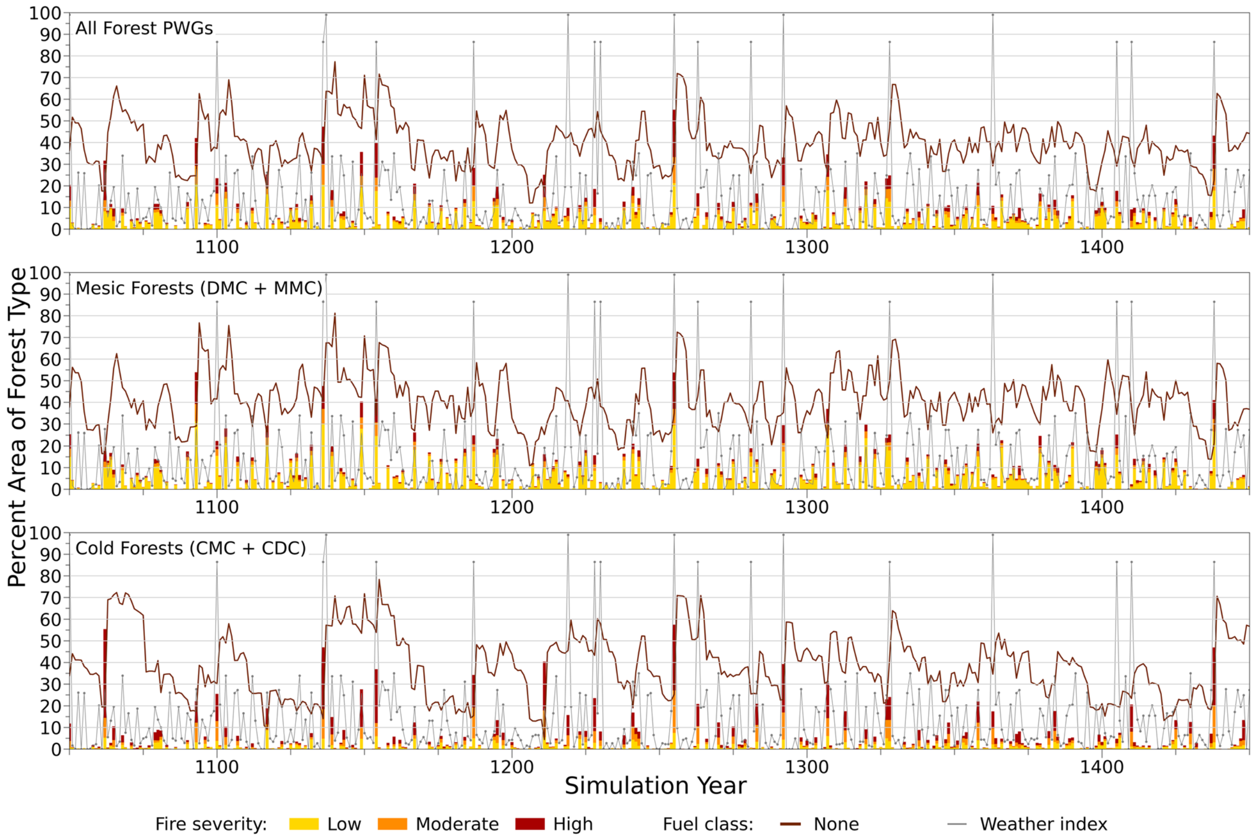

Fig. 4 Relationship of fences and corridors to fire area burned across severities for (top) all PWGs combined, (middle) DMC and MMC PWGs combined, (bottom) CDC and CMC PWGs combined. Note that in each year shown, low-, moderate-, and high-severity fire proportional abundance is shown in yellow, orange, and red coloration in the stacked bars, respectively. Light gray traces depict the weather index (higher numbers indicate more extreme weather years). Dark brown traces show the area in states with recently consumed surface fuels (either of non-forest conditions, post-fire bare ground, or forest conditions that were recently under burned and surface fuels were removed for a time, None)

Classification tree analysis of large fire years (> 20% area burned) Time series plots revealed potential interactions among annual weather, fuel class (as above), and availability to burn, which governed annual area burned and area burned at high severity (Fig. 4). Annual area burned was positively correlated with the weather index (Pearson's correlation coefficient = 0.643), which was a significant predictor of annual area burned (Fig. 5). Visual inspection of Fig. 4 shows a high correspondence between large fire years and extreme weather years, but this was not always the case. In some years, large area burned did not correspond with extreme weather indices and vice versa. Thus, to uncover key interactions between fuels, ignitions, and weather, we focused the analysis on two conditions: Case 1, predicting large fire years that occurred under non-extreme weather years, and Case 2, predicting small fire years that occurred during extreme weather years (Fig. 5).

Extreme weather years were those with a weather index > 87 (98th percentile). The 98th percentile weather index was determined based on the cutoff evident in Fig. 5. Large fire years were identified as those greater than the 95th percentile of area burned (*N* years = 141, area burned = 53,107 ha; ~ 20% of the landscape). This "large fire" size cutoff differed from the previous analyses to capture large, low percentile fire years while ensuring a sufficient sample size for analyses.

We used conditional classification tree analysis to identify a sparse set of predictor variables that best differentiated large fire years from all other fire years (< 20% of landscape burned in a year) under extreme and nominal fire weather years. Predictors included the number of potential ignitions for each year (IGNIT_COUNT), and the percentage of the landscape in each of the three simplified fuel classes (i.e.,

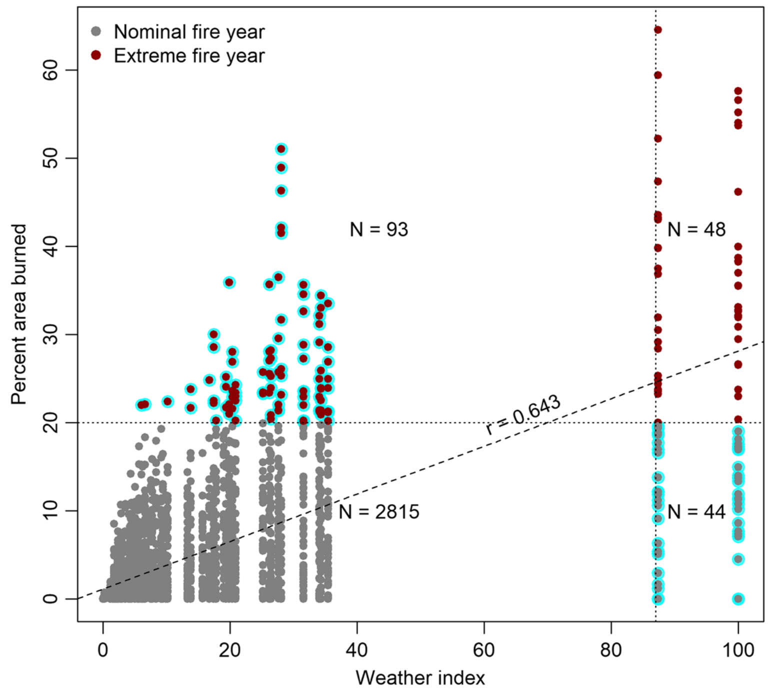

Fig. 5 Scatter plot depicting annual area burned across the range of the weather index used to summarize annual weather conditions across the 3000-year simulation of the REBURN model. The horizontal dotted line represents the 20% area burned threshold (95th percentile) used to differentiate extreme fire years from other nominal fire years. The vertical dotted line is the 98th percentile weather index used to differentiate extreme weather years from nominal weather years. Blue halos represent the points used in subsequent classification tree analyses to identify the drivers of extreme fire years occurring during nominal weather years, and nominal fire years occurring during extreme weather years (see Fig. 11). The best fit regression line for percent area burned as a function of the weather index is depicted with the black dashed line and associated Pearson's correlation coefficient

None, FFE, CFP). This was repeated for high-severity burned area (95th percentile, area burned = 13,547 ha; 4% of the landscape). Conditional classification trees were run using the *ctree* function in the *party* package (v1.2.15; Hothorn et al. 2006, 2015).

Results

A total of 25,331 ignitions were modeled over a 3000-year simulation period, which began after an initial 300-year spin up. Of these, 8563 (34%) were fuel-limited (i.e., landed on a non-burnable substrate or fuelbed) and did not result in a fire, and 16,665 (66%) initiated productive ignitions. The simulated fire size distribution was right skewed, with 70% of fires < 1000 ha and 84% of fires < 4000 ha. Median fire size was 190.3 ha (IQR 1629.7 ha) with a mean of 2300.4 ha (SD: 5594.3 ha) (Fig. S1). Only three fires exceeded the 2006 Tripod Complex fire size (70,894.4 ha), with the largest being 87,877 ha. As of 2022, this would rank as the fifth largest fire in Washington state history. We note that some of the largest fires were potentially truncated by the study area dimensions and bounding box, which may have contributed to underestimating very large fire frequency and maximum fire size. In total, 13.1% of fires intersected the study area perimeter. A total of 25% of the ignited fires reached the 14-day maximum time limit allowed in our model and these fires represented 65% of the area burned over the simulation period. This indicated that most fires were limited by low fuel contagion or by low ERC values and concordant fuel moisture conditions, and much of the landscape was susceptible to burning when these conditions were not limiting.

Average fire return intervals varied by PWG (Fig. 6). Return intervals for DMC and MMC averaged around ~ 17.5 years (range 12–54 years), with little variability in mean value among cells compared to CDC and CMC. For the higher elevation and colder CDC and CMC pathway groups, return intervals averaged ~ 32 years (range 15–88 years), with much larger variation among cells within a PWG.

Question 1. How do patterns and amounts of forest structure and fuels vary across time and space?

At the landscape scale, wavelet analysis (Fig. 7) showed consistency in the power spectra over time with

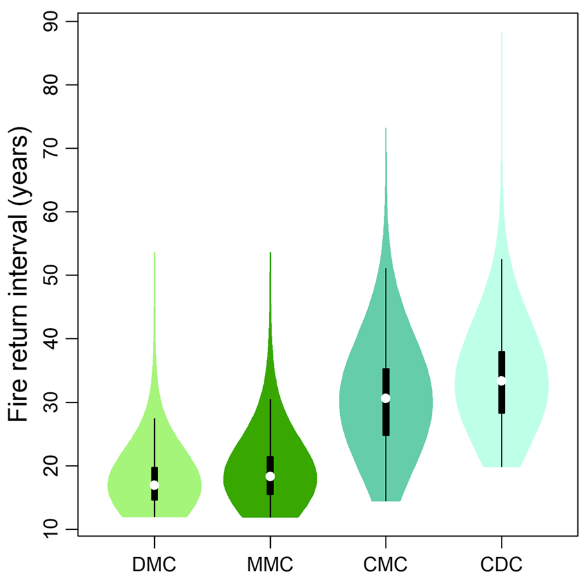

Fig. 6 Violin plots of the variability in percentage area for each structural class within a given pathway group over the 3000-year simulation period. Pathway groups are **A** Dry-mixed conifer-DMC, **B** Moist-mixed conifer-MMC, **C** Cold-dry conifer-CDC, and **D** Cold-moist conifer-CMC. See Table S4 for structure class definitions

significant variations in 8- to 16-year wavelet power for annual area burned, and a mean return interval of 10 years (i.e., wavelet period with highest estimated power). Short-interval power was strongly associated with the 5 to 10-year post-fire vegetation and fuel recovery period, depending on the PWG STM, where fires were not allowed to reburn (i.e., areas showing the post-fire fuel model of NB9, see "Methods"). However, longer periods of low fire activity were observed in the centuries around simulation year 1500 and between years 2000 and 2500, where significance in the power spectra (denoted by black circles) was less apparent (Fig. 7). Short-term patterns of low fire activity were also observed throughout the simulations, indicating that multi-scaled spatial controls on fire activity were likely at work.

Total area burned and high-severity area burned were highly correlated, where large fires generally included the largest area burned at high severity. Correlation between area burned and area burned at high severity was high on both a per-fire basis ($r = 0.84$) and on a per-annual-area-burned basis ($r = 0.92$). Percentage of area burned at high severity for the top 10% of fires by fire size ranged from 1 to 65% (mean 14.7%, SD 13.7%).

Compared to the high-elevation (CMC and CDC) cold forest types, low elevation (DMC and MMC) PWG structural class distributions tended to be more evenly distributed among structure classes over the 3000-year simulation (Fig. 8).

Old forest (OFMS-old forest multi-story, OFSS-old forest single story, O'Hara et al. 1996) occupied ~10% of the low elevation areas, on average, but was consistently <5% of the PWG areas at high elevations. Spatial patterns of old forest showed some areas of high stability (refugia) for both OFMS and OFSS, particularly in the lower elevation sites (Fig. S2). Here, large river drainages, stream confluences, and areas with deeply dissected terrain yielded old forest structures for >40% the simulation period for some cells. Median (area-weighted) age of old forest patches was ~200 years with some variation among types and PWGs (Fig. S3). Across the landscape, old forest patch ages ranged from 140 to 899 years.

Open canopy conditions were dominant in the DMC forest, where SEOC (stem exclusion open canopy, O'Hara et al. 1996) averaged ~20% of the landscape area. YFMS (young forest-multi-story, O'Hara et al. 1996) with relatively open canopy conditions also exhibited greater dominance in drier low elevation than high-elevation forests, where canopies were typically closed. PFBG (post-fire bare ground) and SECC (stem exclusion-closed canopy, O'Hara et al. 1996) were consistently subordinate to other structural conditions in DMC and MMC forests but were often well represented in high-elevation CDC and CMC PWGs.

Low elevation PWGs exhibited a higher level of metastability over space and time, and fewer system-level shifts resulting from large high-severity fire events (Fig. S4). The converse was generally true of high-elevation cold forests. For CDC and CMC pathway groups, presence of OFMS followed a ~300-year cycle, where the percent coverage gradually increased but was then suddenly reduced by large fire events and replaced by post-fire bare ground (PFBG) and stand initiation (SI) structure types (O'Hara et al. 1996).

Question 2. What was the frequency and variability of large fire years?

Principal components analysis of extreme fire years (> 150,000 ha)

Extreme fire years occurred in a total of 8 of 3000 years. Intervals between extreme fire years ranged between 83 and 705 years (mean 321, SD 202 years). Nearest neighbor analysis identified recovery intervals for forest fuel amount and distribution ranged from 30 to 334 years (mean 192, SD 107 years) indicating that in the context of an active fire regime, it required nearly two centuries on average to recover pre-fire conditions following the largest recorded fire years (Fig. 9). The

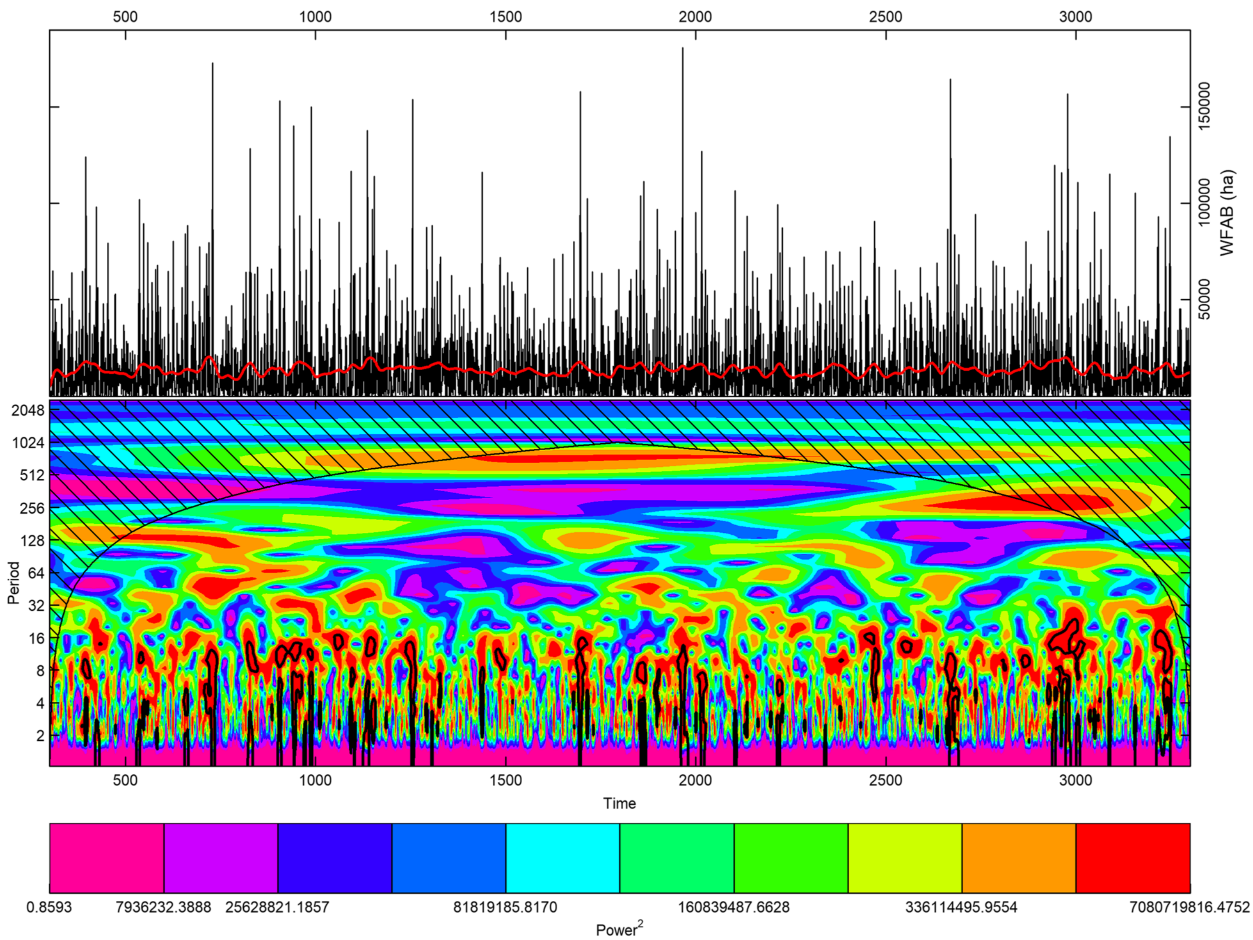

Fig. 7 Time series (top panel) and Morlet wavelet analyses results (bottom panel) for annual area burned for the REBURN model simulation years 300–3300. Wavelet analysis helps identify main periodicities in a time series (here, annual area burned) across multiple temporal scales. The power spectrum (i.e., squared amplitude) for the wavelet analysis is depicted in the color spectrum from low (pink) to high (red) frequency. High power indicates periods of high fire activity, and the black lines identify significant periods of high fire activity, how long those periods lasted (*y*-axis), and the distribution of these periods across the time series

first two principal components (PCs) explained 90% of the variance in landscape composition and configuration. PCA loadings indicated that PC1 strongly coded for the percentage of the landscape in the None fuel class (−0.80), while PC2 reflected the percentage of the landscape in CFP (0.53) and FFE (−0.56) fuel classes as well as IJI or contagion of the None class (0.58). All fires showed similar trajectories from pre-fire landscapes dominated by FFE and CFP fuel classes, to those dominated by None types immediately following a fire (Fig. 9). Pre-fire conditions were clustered near the center of the biplot, largely within the 50th percentile range of conditions, indicating that the largest fires did not occur under rare conditions for structure or contagion (i.e., very connected landscapes with overly dense fuels).

Question 3: What weather, forest structure, and fuel contagion conditions were generally associated with large fire years, and how did surface and canopy fuel contagion, fire weather, and topography interact to drive observed variability of fire size and severity?

Superposed epoch analysis (extreme fire years > 150,000 ha)

Fuel conditions preceding extreme fire years were mostly unexceptional when compared to those across the entire 3000-year simulation. Pre-fire structural conditions were generally within the interquartile range for the simulation period (Fig. 9). In terms of fuel contagion, conditions were characterized by only moderate levels of high crown fire potential (CFP) fuel types (23–34%), fire flow enabling (FFE) fuels (35–43%), and fire fences (None, 27–37%). Large fires transitioned the landscape into predominantly bare ground and sparse fuel type

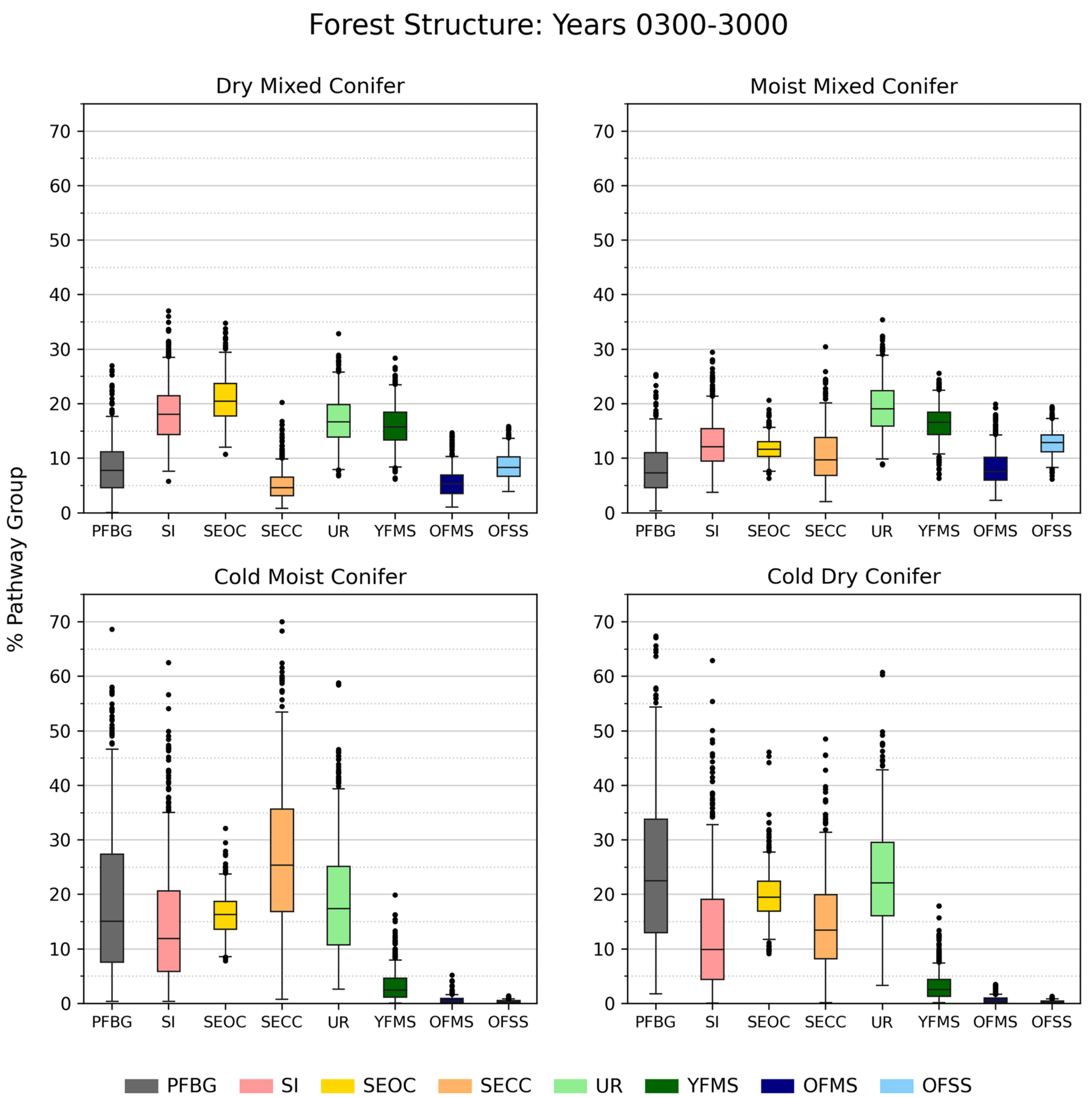

Fig. 8 Box and whisker plots showing the percentage composition of structural classes across the 3000-year REBURN simulation. Abbreviations are DMC = dry-mixed conifer; MMC = moist-mixed conifer; CMC = cold-moist conifer; CDC = cold-dry conifer; PF = post-fire bare ground; SI = stand initiation forest; SEOC = stem exclusion open canopy forest; SECC = stem exclusion closed canopy forest; UR = understory re-initiation forest; YFMS = young forest multi-story; OFMS = old forest multi-story; OFSS = old forest single story. Structure classes are from O'Hara et al. (1996)

(None)-dominated conditions (mean coverage 25%), with little variability in conditions among post-fire landscapes (Figs. 4 and 9).

Superposed epoch analysis (SEA) revealed that extreme fire years were associated with reduced area of the non-burnable (None class) cells for the 3 years leading up to the largest fire years (Fig. 10). These years also corresponded with a significant increase in fire-flow enabling FFE fuel classes during that same period. Percent land of fire fences (the None class) during these pre-fire years was 32–34% of the landscape, and 39–40% in the fire flow enabler (FFE) fuel type. Similarly, the years with the highest area burned at high severity were associated with a reduction in fences to fire spread (None class) and increases in fuels with high crown-fire potential (CFP) up to 4-year prior. Percent land in a high

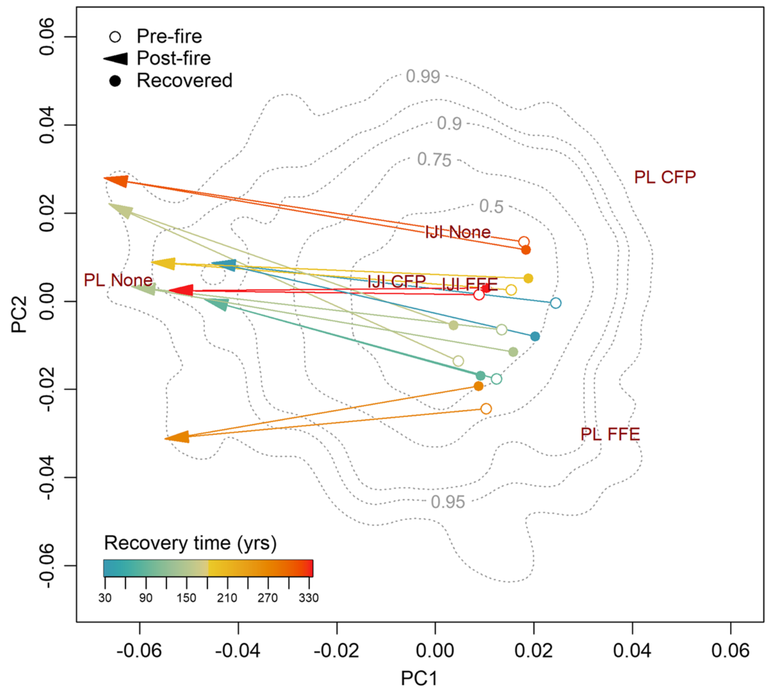

Fig. 9 Forest structure recovery plot for the eight largest fires in the simulation. A principal components analysis was used to depict the annual variability in fuel classes (None, non-burnable and low fire spread; FFE, fire flow enabler; and, CFP, crown fire potential) across the 3000-year simulation period. Two variables (PL, percent land; and IJI, interspersion-juxtaposition index) were used to characterize each fuel class. Percentile conditions across all simulation years are represented in the dotted gray lines. Each pair of colored lines represents the trajectory of the landscape immediately post-fire to its "recovered" state. Open dots represent the conditions present prior to the disturbance; arrows, immediately post-disturbance, and filled dots are the post-disturbance condition closest to the pre-fire condition based on a nearest neighbor analysis. Colors represent the simulation time required to reach a recovered state following the fire

crown fire potential condition prior to large high-severity years was 29–30%.

Following extreme fire years, SEA identified a > 15-year period of significantly reduced percentage area of fuels with high crown-fire potential (CFP). The percentage area in the fire flow enabler (FFE) fuels was also significantly reduced for 5–10 years following extreme fire years. Fire fences significantly increased in area for up to 10 years following extreme fire years; the post-fire vegetation recovery period that was integrated into the model.

Classification tree analysis of large fire years (> 20% area burned)

While weather was the leading driver of total area burned and area burned at high severity (Fig. 5), other factors contributed to both reducing fire activity under extreme weather conditions and facilitating increased fire spread and severity under nominal weather years. In both cases, classification tree analysis indicated that the number of annual ignitions and the percentage of the landscape in the "None" fuel class (i.e., fire fences) were largely responsible for governing fire activity.

In Case 1 (i.e., low fire activity during extreme weather years; Fig. 11A), annual area burned was limited largely by the lack of ignitions. When ignitions were not limiting, however, area burned was still limited when the landscape was composed of >40% in the None fuel type (Table S4).

Similarly, in Case 2 (i.e., high fire activity in nominal weather years; Fig. 11B), large fire years were observed only when both ignitions and fuel connectivity were not limiting. Even with ample ignitions, burned area was limited when the landscape had >24–27% in the None fuel type. Therefore, compared to nominal weather years, extreme fire years only required fences to account for *~15% more of the landscape* to effectively reduce the probability of a large fire year. These values were generally consistent across PWGs (Table 1).

Discussion

Historical fire regimes in eastern Washington, USA, and likely elsewhere in wNA appear to have been self-regulating, mediated by wildfire disturbances, especially during periods of relatively stationary climate. These relations were facilitated through interactions over space

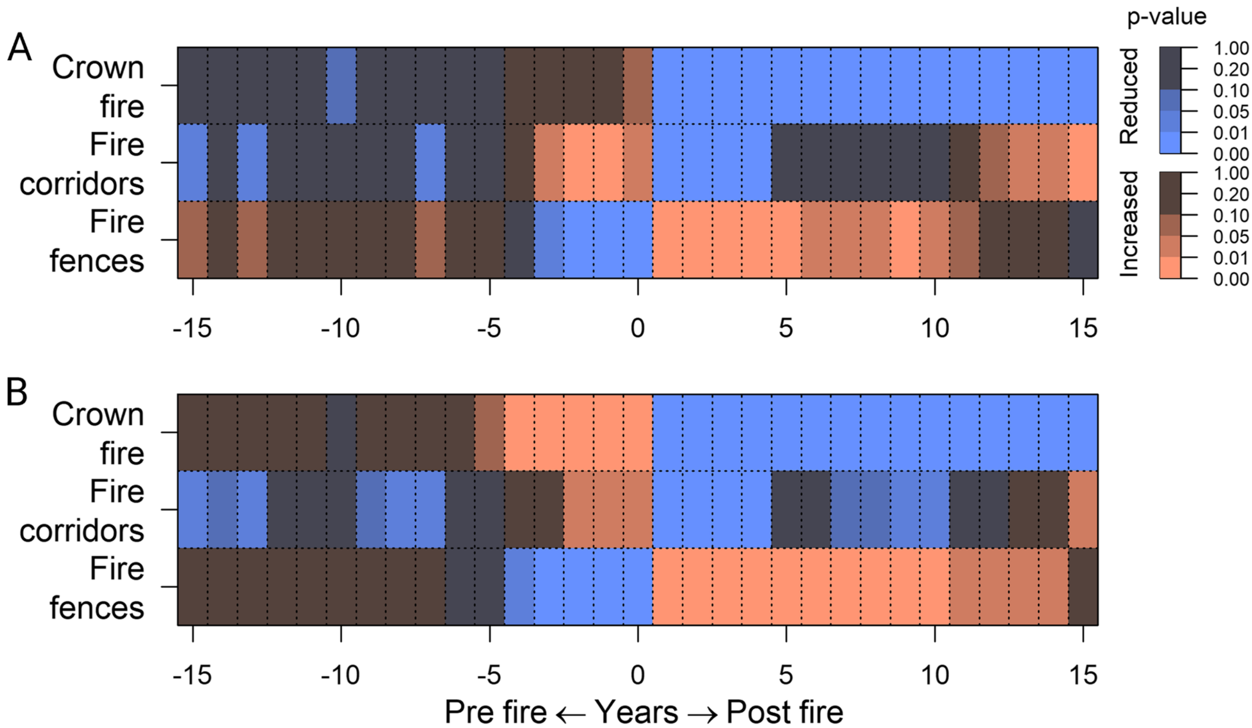

Fig. 10 Superposed epoch analysis results identifying significant departures in landscape fuel conditions leading up to and succeeding large fire years. Pink blocks indicate fuels were more abundant a given year prior to, concurrent with, or following a large fire year compared to all other years. Similarly, blue blocks indicate less abundance of a given fuel class. Brighter colors indicate higher significance. **A** Percent land of fuel classes for simulation years where total area burned > 150,000 ha, **B** percent land for fuel classes for years where high-severity fire area > 40,000 ha. In each panel, Fire fences refers to the None fuel class; Fire corridors refer to Fire Flow Enabler fuel classes (FFE); and Crown fire refers to high crown fire potential (CFP) fuel classes

and time between ignition patterns (both intentional Indigenous and naturally derived), past burn severity patterns, and resulting successional and fuel dynamics (Hessburg et al. 2019; Prichard et al. 2017, 2021). Our ability to empirically study these dynamics is inherently hampered by a lack of data needed at all relevant scales, with adequate fidelity to identify multi-scaled patterns and interactions between vegetation, fire, and climate (Keane et al. 2009). Many theoretical models exist to describe behavior in complex systems, each differing in the assumptions driving behavior (Malamud et al. 1998, 2005; Moritz et al. 2005, 2011). However, each model falls short of capturing the variability and complexity of fire behavior, fire spread, vegetation and fuel responses, and multi-level feedbacks exhibited at each impacted scale (Reed and McKelvey 2002).

The REBURN model was designed to test these relationships over large spatial (1000 s to 10,000 s km^2) and deep temporal (100 s–1000 s year) scales using customized vegetation state-transition models and daily weather streams of an actual large landscape. Modeling system-level dynamics at cell to patch to regional landscape levels enables us to capture the influences of relevant top-down conditions and processes that can drive large wildfire events, and bottom-up conditions and processes that can also exert key spatial and temporal controls on system behavior. Our main findings from the 3000-year simulation period were that:

(1) System properties exhibited a high degree of metastability, and forest structural patterns were well within observed, empirically reconstructed, early twentieth century conditions (see Prichard et al. 2023 for a breakdown of that discussion).
(2) Fire weather was the main determinant of annual area burned, but ignitions and landscape fences (i.e., fuel barriers to spread) provided strong spatial and temporal controls on fire size and severity.
(3) Large fires were integral to these systems. They modestly increased dominance of high-severity fire, which increased abundance of non-forest and early successional types, and lengthened recovery times.
(4) Non-forest conditions appear to be a vital element of metastability conditions.

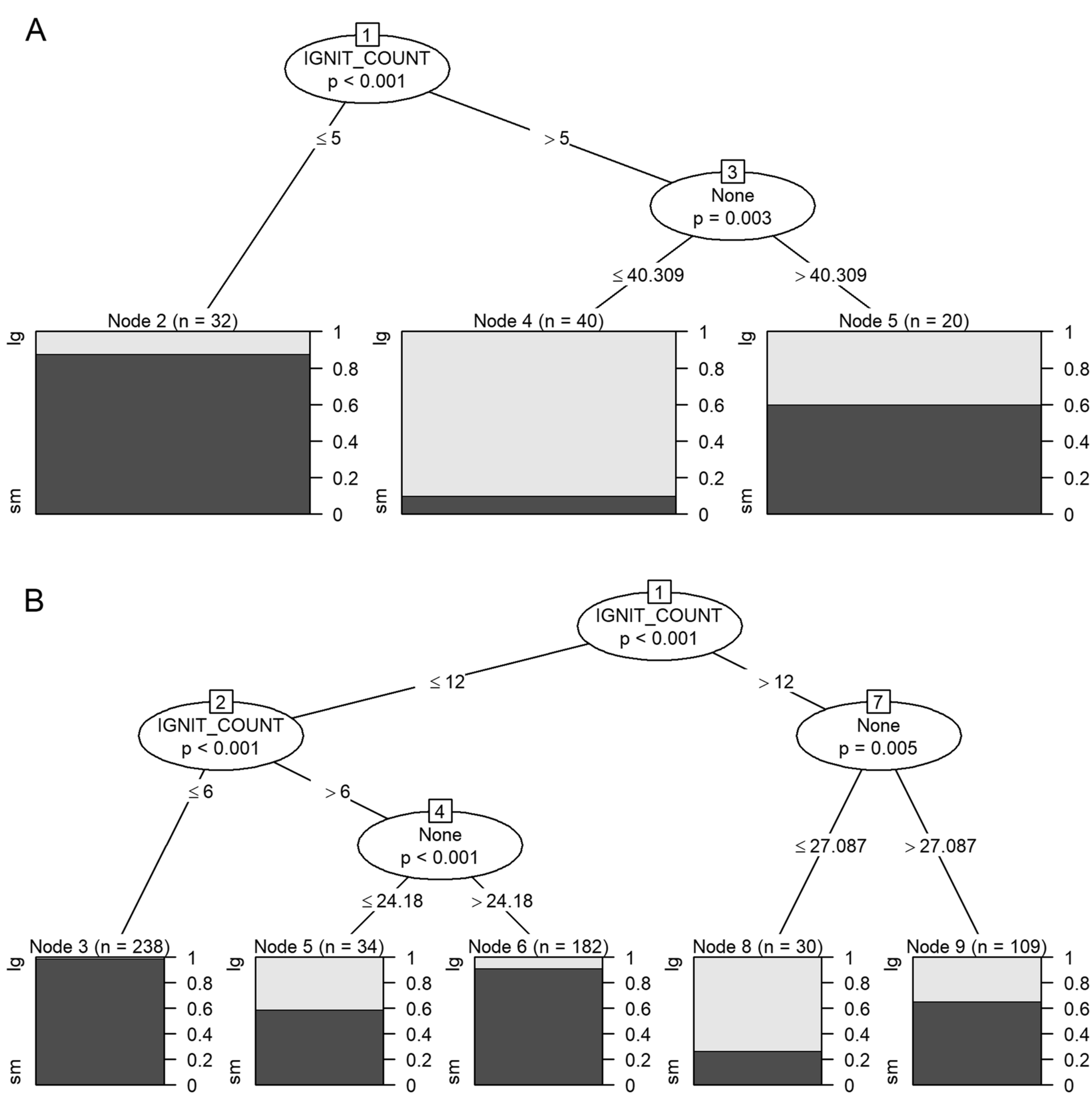

Fig. 11 Conditional classification trees used to identify the main drivers associated with **A** low fire activity during extreme weather years and **B** high fire activity during non-extreme weather years. Extreme fire weather were years with weather indices > 83 (98th percentile). High fire activity (lg, light gray) years were those where > 20% of the landscape burned (95th percentile) and low fire activity (sm, dark gray) years were those where < 20% of the landscape burned. In both models, the number of ignitions (IGNIT_COUNT) and the percentage of the study area in the None fuel class (i.e., non-burnable or low flame length and rate-of-spread fuels) were the main drivers of fire activity

(5) Fires were integral to low- and high-elevation forest dynamics. Despite differences in fire regime properties, spatial and temporal controls on large fire years were similar, which indicated that key connections across environmental gradients and forest types were continuously occurring.

The role of fences and corridors in system-level dynamics

Evidence continues to mount regarding the ability for reburns (and forest restoration treatments that emulate them) to effectively mitigate fire spread and severity at local scales (Prichard et al. 2021). However, questions remain as to how these effects may be scaled

Table 1 Results from conditional classification tree (CTREE) analysis indicating cutoffs determining the effective area in landscape fences (i.e., None fuel class) above which the probability of large fire was lowered during both nominal (< 98th percentile) and extreme (> 98th percentile) fire weather years

Forest type	Response	Area in fences (%)	
		Nominal weather	Extreme weather
All types	Annual area burned	27	40
All types	High-severity area burned	24	40
High elevation	Annual area burned	38	47
High elevation	High-severity area burned	38	47
Low elevation	Annual area burned	35	39
Low elevation	High-severity area burned	35[a]	47

[a] CTREE algorithm did not find a significant break

up to influence system-level fire behavior and vegetation dynamics (Prichard et al. 2017; Stevens-Rumann et al. 2016; Stephens et al. 2021). Our REBURN model demonstrates the large contribution of fire fences to regulating system-level wildfire activity, including the frequency of large fires and large fire years. Under both nominal and extreme (> 98th percentile) weather years, the distribution of fire fences on the landscape was a main determinant of annual area burned and area burned at high severity.

Moreover, we identified a critical threshold of abundance for fire fences, where >40% of the landscape in these fuel types effectively reduced the probability of large fire years, even during extreme weather years with ample ignitions. Under moderate fire years, this estimate was reduced to 25% of the landscape. Thus, extreme fire weather years only required a ~15% increase in fire fences to reduce the probability of a large fire year compared to nominal weather years. This finding agrees with the treatment levels recommended by Finney (2007) who suggested that landscapes with 30–40% area treated can effectively reduce fire size and spread rate, where spatial optimization is not possible or impractical. In our simulations, the active fire regime of our landscape maintained >40% area in fire fences for 1500 years (i.e., half the simulation period), values that match well with data from the Northern Glaciated Mountains province (Table 1 in Hessburg et al. 2019).

Other studies show similar landscape-level benefits from treatments, but at lower treatment levels. For example, Collins et al. (2013) found that treating 20% of a 19,000-ha study area in the northern Sierras reduced modeled fire size and the occurrence of high-severity fire. Stevens et al. (2016) showed no substantial reduction in area with high potential flame lengths between treating 13 vs 30% of an 8000-ha watershed in the Lake Tahoe Basin. The REBURN model results reported here corroborate results from these and other studies (Ager et al. 2010; Syphard et al. 2011) and demonstrate the importance of fire fences to reducing the likelihood of large and severe fires.

Historically, the abundance and interspersion of fences to fire flow was critical to influencing wildfire activity. Vegetation types with low rates of spread provided large landscapes with the capacity to maintain a kind of balance in the potential energy stored in landscape fuels such that structure and function were metastable over space and time. However, the amount and configuration of these types likely varied over space and time. Hessburg et al. (2019; Table 1) reconstructed how bare ground and non-forest abundance varied from province to province. For example, the Upper Klamath province had as much as 71% land in non-forests in pre-management era forested landscapes, while the Southern Cascades Mountains province displayed as little as 25%. The non-forest conditions required to stabilize fire regimes under the twenty-first century climatic warming will likely increase (Hessburg et al. 2019), and those increases will again be conditioned by physiographic domain.

The mean longevity of fire fences influences how the patchwork of time-since-fire conditions reduced future fire spread and severity. Our wavelet analysis showed a strong power signal within the range of 8 to 16 years for most of the simulation period, with some brief periods of more and less frequent wildfire activity. This system-level behavior is a result of both inherent constraints on wildfire spread (burns stop at fences) and emergent properties of fire-vegetation and fire-fire feedbacks. For example, moderate fire severity reduces canopy bulk density and fuel ladders for a time. In contrast, low-severity fire eliminates fuel ladders and elevates crown bases such that longer flames are required in a future fire to ignite crown bases (Agee and Skinner 2005).

We imposed a 5- to 15-year refractory period (depending on the STM), where past fires impeded future fire spread through the conversion of a burnable to a non-burnable (NB9) surface fuel model. This interval corresponds well with the findings of Parks et al. (2015a), who found that fires effectively inhibited fire spread for 6–18 years within western US wilderness areas. Similarly, Buma et al. (2020) found fire-fire interactions prevented subsequent burning for 10–20 years across much of the western USA. Prichard and Kennedy (2014) similarly found that past wildfires in the interior Pacific Northwest can inhibit future fire spread for up to 34 years, suggesting potentially stronger landscape memory in this region than we have shown. By modeling this inhibitory constraint over space and time, we revealed the central importance of fire-fire and fire-vegetation interactions in driving long-term system dynamics. Future climate change will likely challenge the longevity of landscape memory over space and time, particularly when extreme drought persists across regions or where teleconnections between terrestrial and atmospheric processes lead to plume-dominated spread events (Peterson et al. 2021). However, with increasing regeneration failures after large and severe fires (Coop et al. 2020; Davis et al. 2023), we may expect longer refractory periods within some regions in the future (Hessburg et al. 2019).

In our simulations, fire return intervals were an emergent property resulting from interactions among ignitions, weather, vegetation and fuel configurations, and topography. Despite the observed fire intervals across the simulation period, simulations exhibited quite high levels of spatial and temporal variability in local fire return intervals and fire effects, structural class distributions, and landscape-level contagion; all features we would expect from landscapes with active fire regimes. For example, we were able to observe fire refugia on the landscape where old forests would obtain and often last for centuries, despite the high abundance of wildfires in surrounding terrains (see below).

Reburning was integral to the fire regime in the simulations, with some cells burning > 300 times during the 3000-year period. Return intervals varied across PWGs, with lower elevation dry forests burning once every 12 to 54 years with relatively low variability, and upper elevation cold forests burning every 15 to 88 years with high variability. These intervals correspond well with estimates of historical fire frequency in the region (Everett et al. 2000; Wright and Agee 2004).

Work by Hessl et al. (2004) in this region showed that variability in fire return intervals may be associated with warm and cool phases of the Pacific Decadal Oscillation (PDO), which would contribute additional variability to median and mean fire return intervals, and their ranges. Long-term influences from these oscillations were not integrated into the REBURN model at this time; however, they will be in future work.

Large fires within the context of reburning landscapes

Our REBURN simulations demonstrated a high capacity for the landscape to respond to and rebound from large fire disturbances. Fires approximating the size of Tripod (70,000 ha) occurred once every 37 years on average, suggesting that large fires were a common component of this system. The largest fires in our simulation (> 150,000 ha) were twice as large as the 2006 Tripod Complex, occurred at irregular intervals between 80 and 700 years (mean 320 years), and caused widespread transitions from forest to bare ground and early seral types.

While the largest fires contributed the largest area in stand replacement fire, much of the fire footprint of these fires exhibited complex spatial patterns of fire severity, offering added, rather than reduced, complexity to the landscape. Hence, large fires at characteristic frequency in this landscape are not necessarily indicative of a decline in resilience. Recovery times from these largest, hottest fires were generally on the scale of one-to-many centuries. Thus, after some large fires, residence time in alternative stable states, including post-fire grasslands and shrublands, can be extensive and an ordinary part of resilient ecosystems with active fire regimes. However, a substantive change in large and severe fire frequency can undermine long-term landscape resilience and the regrowth of forests (Buma et al. 2020, 2022).

Long recovery periods after large fires in our simulations restricted subsequent large fire growth and allowed more localized fire effects to play out in discrete portions of the landscape. These largest fires were the most severe, but they also contributed, not just structural heterogeneity, but (1) large areas of short-term non-high-severity fences, (2) reduced fuels because of the 10- to 15-year post-fire refractory period, and (3) transitions to states less conducive to fire flow. For example, the largest fire in our simulation included over 58,000 ha of low- to moderate-severity burned area. As such, large fires can reset the successional time clock across large areas and increase spatial heterogeneity in forest structural conditions elsewhere.

In our simulations, the patchwork of high fuel load contagion at the largest landscape scale was dynamic and that in turn influenced future fire spread and severity. In our landscape, where an active fire regime was allowed, we observed that resilience after occasional large fires recovered via the occurrence of numerous small- to medium-sized interacting reburns that restored landscape complexity and a common range of conditions (Moritz et al. 2005, 2011; Loehman et al. 2020).

REBURN's system-level behavior was largely driven by interactions between the amount and distribution of ignitions, the shifting landscape mosaic of fuel condition, and the frequency of extreme and non-extreme weather years. Large fire years were an integral component of observed system-level dynamics and temporal trends, and system recovery was not ensured by our model. Instead, recovery was an emergent outcome of system-level fire-fire and fire-vegetation interactions. Taken together, the Tripod landscape showed a consistently strong basin of attraction representing a high probability of ordinary vegetation state representativeness.

While weather was the leading determinant of annual area burned, our analyses clearly showed that the presence of extreme weather years alone did not ensure large annual area burned. During many of these years, *a lack of ignitions* (i.e., < 6 per year) often restricted the probability of a large fire year, even when landscape fuel contagion and susceptibility to large fire activity were high. When ignitions were not limiting, the abundance of fire fences provided control on fire activity when conditions were otherwise primed for a large fire year. Such controls on fire spread and severity enabled small- and medium-sized fires to play an outsized role in steadily chipping away at landscape contagion, when large fire years failed to develop. Interestingly, the eight largest fires ignited on landscapes with unexceptional fuel patterns, countering our expectation that such fires would be initiated through rare fuel conditions.

The complex landscape dynamics derived in REBURN from climate, fire, vegetation, and fuel interactions suggest that the buildup of fuels just above ordinary stabilized conditions (those within the IQR) does not always portend large fire activity. This observation suggests that simpler representations of system-level dynamics will miss key feedbacks and their ability to influence fire activity over space and time. Similarly, extreme weather years alone are insufficient at ensuring large fire years, signifying a key role for other spatial and temporal controls, including fuel amount and its connectivity, and the lagged influence of fire disturbances on fuel recovery and its contagion influences. In our simulations, large fires played an important role in system dynamics. Given that role, the opportunity to "skip" large fire years has implications that can last for one to several centuries. Large burned area, with high variation in fire severity patterns is an asset to the long-term structure and processes of large landscapes.

The amount, distribution, and timing of human and natural ignitions is a main driver of historical and modern fire regimes in wNA (Taylor et al. 2016; Balch et al. 2017; Keeley et al. 2021; Hantson et al. 2022; Knight et al. 2022). In the context of modern fire regimes, human ignitions are often associated with large and severe fires, mainly as they occur close to population centers, often coinciding with extreme weather conditions that facilitate their spread.

In sharp contrast, Indigenous cultural burning practices—prior to Euro-American settler colonization—provided abundant ignitions that promoted highly reburned landscapes. These ignitions were timed and placed with skill to remove fine fuels and understory biomass to improve controls on future fire sizes and their severities (Knight et al. 2022). Cultural burning and reburning was conducted when fine fuel moistures approached moistures of extinction during shoulder seasons or within the fire season. Shifts in fire frequency over the past 150 years are linked to large losses in culturally burned area and fire suppression practices rather than long-term variability in fire-climate relations (Hagmann et al. 2021; Taylor et al. 2016; Roos et al. 2022). Our results support the crucial role that well-timed, high-frequency ignitions have on regulating fire size and severity over large landscapes.

Landscape fire connections between low-elevation and high-elevation forests

The Tripod study area, like many mountainous landscapes of wNA, spans steep elevational gradients and deeply dissected terrains, which contribute to fine- and broad-scaled variability in forest types and subsequent fire regime characteristics. Cold forests represented 30% of the study area, and yet they exerted an outsized influence on fire size distributions and consequences for landscape patterns. These forests have been characterized by relatively infrequent, high-severity fires (Agee 1996; Bessie and Johnson 1995). However, high-elevation cold forests in the Tripod region are characterized by moderately infrequent to frequent, moderate-, and high-severity fires (Agee 1996, 2003; Halofsky et al 2020). These forests are generally observed to be ignition limited, fires are strongly weather driven, and most area burns under continuous dry and hot conditions (Bessie and Johnson 1995). As a result, cold forests will likely undergo considerable changes with continued warming (Cansler and McKenzie 2014). In the Pacific Northwest, Halofsky et al. (2020) suggests that fire frequency in high-elevation forests will increase with no attendant decrease in severity, potentially heralding rapid changes in forest structure and composition, and in the amount and distribution of non-forest physiognomies.

Absent climate change considerations, our results agree with prior research. Fire at higher elevations was driven by weather periods favorable to fire ignition and spread. As a result, fire return intervals were more variable in cold forests than lower elevation forests, and fires on average reached a given cell once every 30 years, often at high severity. Most fires were small- to medium-sized, but large fires burned the most area. Over 3000 years, this resulted in high-elevation cells experiencing fire ~ 100 times on average. Based on mean fire return intervals, large fire years (when > 20% high-elevation forest burned) occurred once every 25 years, and very large fire years (> 50% area burned) occurred once every 270 years. Cold forests (CDC and CMC combined) had nearly four times the number of high-severity fires on average (45% vs 12% for DMC and MMC combined) despite an only 10-year longer average return interval. We note that the highest lightning probabilities occurred at these higher elevations, and as such, fire frequency was not limited by ignitions but by *unfavorable* weather conditions for burning along with non-contiguous fuels receptive to crown-fire spread.

Given the large disparity in climate and weather conditions between low- and high-elevation forests, we tempered REBURN fire spread and expected flame lengths in the high elevations by using alternative fuel models for the cold forest types, when ERCs were generally low for a given weather day (Prichard et al. 2023). This mimicked the correspondence of actual fire occurrence at high elevations with conducive fire weather conditions. Under lower ERC days, fires were allowed to burn, but surface fuels were generally less receptive to crown fire initiation and spread. As a result, high-elevation forests occasionally acted as a deterrent to large fire growth because fuel beds impeded fire spread. Large fires occurred under nominal fire weather conditions, but they required either windows of high ERC values for fires to permeate through high-elevation forests, or for fires to burn around high-elevation forests. Our model results showed that cold forests in this area burned with moderate frequency and that fire severity was spatially and temporally mixed. Furthermore, a diversity of forest ages and patch sizes were maintained where large fire frequency was low through reburning.

Early seral (post-fire bare ground (PFBG) and stand initiation (SI) states combined) conditions were also abundant (ranging from 9 to 49%), and some discrete forest-capable areas persisted in these states because of reburning, in all forest types. These early seral patches provided heterogeneity in forest-capable settings, which is important to fostering wildlife habitat complexity (Swanson et al. 2011, 2014). It is also key to influencing fire spread and severity patterns by reducing flame lengths and the potential for crown fire initiation and spread (Hessburg et al. 2016, 2019; Prichard et al. 2017). Median residence times for these early seral conditions varied between 15 and 36% of the simulation period (450 to 1080 years). However, some areas remained in this condition for > 1200 years. In recent work, Hessburg et al. (2019) found that 43% of the area in this province (the Northern Glaciated Mountains) was in an early seral condition (PFBG, SI, herbland, shrubland, or woodland) before settler colonization, active fire suppression, and timber management. Of non-forest areas within this province, 77% occurred in forest-capable environments.

Spatiotemporal dynamics of old forest refugia

Overlapping fire patterns and the resulting spatial redistribution of structural conditions yielded continuously shifting landscape mosaics. Topographic controls on fire spread and severity were strongly evident through (1) fine-scale spatial variability in topo-edaphically entrained PWGs, (2) greater flame lengths and rates of spread on steep slopes during fire events, and (3) fire flow routing and interruption by certain landforms across the study area. Patterns of fuel complexes and topography led to complex spatial patterns in locally dominant and semi-persistent late-successional and old structural conditions, i.e., fire refugia (sensu Camp et al. 1997). For example, the presence of old forest multi-story (OFMS) structure in our model required a minimum fire-free period of 40 years in an old forest single-story state (OFSS). In dry forests, this equated to 2 or more missed fire cycles given the mean fire return interval in these types. Overall, OFMS occupied a minor fraction of the Tripod landscape, owing to high fire frequency and an abundance of moderate-severity fires (Fig. 6). In most cases, large old trees were a widespread remnant of a former forest condition. This is consistent with what Hessburg et al. (1999, 2000a, b) found for this region in their large landscape assessment. However, in topographically influenced fire shadows, we noted generally frequent emergence of fire refugia with implications for future wildland fire management that can maintain old forest structure and associated wildlife habitat.

In low elevation dry forest types (DMC), approximately 15% of the landscape retained OFMS and OFSS structure for ≥ 300 years. This finding is consistent with those of Agee (2003). In contrast, OFMS and OFSS abundance in cold forests occurred on < 1% of cells for this duration. These results indicate that the fine- to meso-scale heterogeneity provided by topography within frequent fire systems of low elevation forests (see Kellogg et al. 2008) was less influential at higher elevations, where severe fires were driven more strongly by fire weather, and forest structure with widespread fuel ladders was conducive to stand replacement.

Elsewhere, a large patch of stable OFMS resided in a large cirque basin located in the southeast portion of the landscape, in an upper headwall fire refugium (Fig. S2). This area was uniquely sheltered from fire by a long north–south oriented ridge, and away from the dominant west to east wind routed paths of fire spread. Topographically entrained fire refugia are key components to the landscape given their higher likelihood of persistence. They also contribute to post-fire landscapes by providing reliable seed sources and bridging habitat while forests recover (Vanbianchi et al. 2017a, b; Camp et al. 1997; Meddens et al. 2018; Larson et al. 2022). Our results also showed that old forest, once they obtained on the landscape, persisted for ~ 200 years on average, which was fairly consistent across PWGs. However, old forest was a rare feature at high elevation (Fig. S2).

Management implications

Within this study region, marked departures from historical fire regimes have created a fire deficit in many fire-adapted landscapes (Haugo et al. 2019; Parks et al. 2015b). Forests that once experienced frequent low- or moderate-severity fires are now more susceptible to high-severity fire events, where most trees are killed (Hagmann et al. 2021). With the wicked problem posed by rapid climate change (Dennison et al. 2014; Marlon et al. 2012; Abatzoglou and Williams 2016) and the increasing frequency and severity of large fires, land managers need coherent guidance for adapting landscapes to fire and climate change. This is especially necessary under the influence of escalating climatic warming, wherein many more forests will be visited by wildfires (Anderegg et al. 2021), and without which, many post-fire conditions will fall short of meeting expectations for desired human, forest, native plant, and animal habitats.

Our REBURN modeling results confirm that landscape memory from recurrent fires is strong in fire-frequent low- and moderate-severity fire-dominated PWGs and integral to their resilience (Peterson 2002). Multi-millennial simulations showed us that forest reburning across all types is not exceptional, but an organizing principle of resilient forest landscapes. At meso-scales (~ 10^2–10^4 ha), fire event sizes are clearly influenced by a mixture of both endogenous and exogenous controlling factors (Turner 1989; Moritz et al. 2011) and it is in this so-called "middle numbers region" that human influence can be most effective at reducing the frequency of larger fires to more characteristic levels. Main influences would be to introduce and maintain intermediate levels of disturbances in small to moderate patches (e.g., 50–5000 ha). Doing so may result in tamping down the frequency of the largest and most severe future events. Cultural burning practices, prescribed burning, forest thinning with prescribed burning, and managed wildfires can all be used to rebuild these patch sizes and patterns on landscapes that evolved with an active fire regime.

Under twentieth century climate and weather conditions, REBURN modeling revealed that fences to fire flow (our None class) occupied > 40% of the landscape over about half of the simulation period and that the amount and interspersion of this area was critical to reducing the probability of large and severe fires, even in extreme fire weather years. Where optimal treatment placement could be realized, this percentage could be reduced to 20 or 25% (Finney 2007); however, the opportunity for spatial optimization is challenged given existing land allocations, ownerships, and stationary habitat commitments.

Model assumptions

As with all models, results from our REBURN simulations should be considered in the context of model assumptions and limitations. Most fire growth models, including FSPro, do not incorporate or consider large fuel (≥ 1000-h timelag fuels) amount and aridity in their spread algorithms, which can, under certain circumstances, contribute to large and intense fires, and extreme smoke emission factors during extreme fire weather. Furthermore, to the best of our knowledge, no operational fire growth models for large landscape simulations can incorporate plume-driven fire behavior or spotting ignitions from pyrocumulonimbus clouds, which have been associated with some of the most extreme fire growth days (Peterson et al. 2021). FSPro is no exception, but work is in progress.

We did not invoke fire spotting in our simulations. Initial runs showed that spotting led to consistently extreme fire sizes that were not easily remedied through changes in parametrization of other aspects of the model. We expect that these influences are quite modest for small and medium-sized fires but are likely greater for wind-driven extreme fire events. However, our fire size distributions did not reflect a major impact of this lack of fire spotting (Fig. S1).

Similarly, modeled fire event duration was defined by two specific stopping rules that were set to limit the frequency of fire sizes observed in initial model runs that were inconsistent with the historical data and fire size distributions for the same period. These rules included stopping a fire after two consecutive ERC days below 55, which is consistent with observations, or a maximum duration of 14 days, which seemed quite reasonable considering that most large fires burn most of the area in 2–5 burn periods (Coop et al. 2022; Finney et al. 2009).

The REBURN STMs currently do not incorporate spatial seed dispersal processes and regeneration is assumed after 5–15 years. Seed dispersal is a key limiting factor for many conifer species in large high-severity patches (Stevens-Rumann and Morgan 2018; Littlefield et al. 2020; Povak et al. 2020). Incorporating seed dispersal processes would likely increase the refractory period, further delaying forest development after the largest and most severe fire events. However, even lacking a seed dispersal algorithm, we found highly similar results in the amount of non-forest area and their patch size distributions as prior studies in this region. We note that effects of this omission would likely vary regionally, largely related to geographically specific soils, lithologies, plant available water relations, climatic water deficit relations, and post-fire shrub responses that can contribute to long-term state conversions (e.g., in the central Sierra Nevada in California) but not in others (e.g., eastern Cascades and

Okanogan Highlands of Washington) (Coppoletta et al. 2016; Coop et al. 2020; Povak et al. 2020).

Finally, given the 90-m resolution of simulated landscapes, REBURN does not account for density-dependent mortality and resource partitioning among cohorts within cells. However, these processes likely have a more limited influence on system-level dynamics over very large spatial and temporal scales. The 0.81-ha cell resolution also misses fine-grained refugia that other studies document (Meddens et al. 2018) but add up to little area.

Future research

The goal of regional landscape fire simulation models is to capture key variability in terrestrial and atmospheric processes, conditions, and interactions that drive large system-level dynamics. Resulting outputs can then be used to characterize resilient from non-resilient vegetation patterns and conditions, and related fire regime properties under a given climatic regime, for a geography of interest. Models can also be used to simulate alternative future successional trajectories, large landscape structure and (re)organization, and disturbance interactions under various climate change and management scenarios. Disentangling the relative influence of each factor can improve our understanding of the roles that fire exclusion and reduced cultural burning historically played in altering the characteristics of active fire regimes, and the role that adaptive management can play in mitigating negative future socioecological consequences.

These original REBURN simulations intentionally did not incorporate climate change. However, under a warming climate, these observations will likely undergo significant shifts, and thus, benchmark simulations like those reported here were necessary. As fire-prone ecosystems across the globe undergo rapid changes, system-level responses to increases in human and lightning ignitions, area burned, and area severely burned will likely create more permanent system-level shifts to alternative stable states over large areas, or forest regeneration periods may be long with concomitant impacts to wildlife habitat, carbon storage, and other ecosystem values. Our future research direction is to simulate warming trends across the twenty-first century to discover shifts in stabilizing conditions and potential bifurcations in system-level dynamics.

With REBURN in the Tripod area, we noted that neighborhood effects on fire regime variability between forest types (PWGs) were sizable and influenced the landscape ecology of fire to a large degree. The utilities available in REBURN enabled us to make both practical and theoretical inferences about historical wildfire regimes in the simulation landscape, and to make inferences about system-level behavior and changes in the dominant drivers of fire patterns and vegetation responses across space and through time.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-023-00197-0.

Additional file 1: Figure S1. Fire size distribution for all fires that burned over the 3,000-year simulation. Power law and log-normal distributions were fit to find the best-fit region of the data to each model using methods from Clauset et al. (2009). **Figure S2.** Maps depicting spatial heterogeneity in the residence time (percentage of 3,000-year simulation period) of various old-forest structural classes including A) old-forest multistoried (OFMS) and old-forest single-story (OFSS) combined, B) OFMS only, and C) OFSS only. **Figure S3.** Average stand age for old-forest structural classes for simulation years 800-3300. Abbreviations are OFMS, old-forest multistoried, and OFSS, old-forest single story. **Figure S4.** Time-series of structural classes over the 3,000 simulation years for the Tripod complex study area – companion to Fig. 4 in the text. Structure classes are PFBG: post-fire bare ground, SI: stand initiation, SEOC: stem-exclusion open canopy, SECC: stem-exclusion closed canopy, UR: understory re-initiation, YFMS: young forest multi-storied, OFMS: old-forest multi-storied, OFSS: old-forest single-storied. PWG is pathway group and represents unique state-and-transition pathways designed for forests varying in productivity, fire regimes and/or species assemblages. Dry forests are DMC: dry mixed conifer, MMC: moist mixed conifer and cold forests are CMC: cold mixed conifer, and CDC: cold-dry conifer. **Table S1.** Surface and canopy fuel properties of dry mixed conifer (DMC) and moist mixed conifer (MMC) states. CC = canopy cover (%), CH = canopy height (m), canopy base height (m), crown bulk density (kg m^{-3}). Fire hazard classes are FFE: Fire flow enabler, CFP: Crown fire potential, and None: none burnable or low flame length/low rate of spread. **Table S2.** Surface and canopy fuel properties of cold dry conifer (CDC) and cold moist conifer (CMC) states. CC = canopy cover (%), CH = canopy height (m), CBH = canopy base height (m), CBD = crown bulk density (kg m^{-3}). Fire hazard classes are FFE: Fire flow enabler, CFP: Crown fire potential, and None: none burnable or low flame length/low rate of spread. **Table S3.** Surface and canopy fuel properties of states that are not within a STM pathway. CC = canopy cover (%), CH = canopy height (m), CBH = canopy base height (m), CBD = crown bulk density (kg m^{-3}). Fire hazard classes are FFE: Fire flow enabler, CFP: Crown fire potential, and None: none burnable or low flame length/low rate of spread. **Table S4.** Abbreviations and definitions of pathway groups, forest structural classes and landscape metrics.

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Authors' contributions
NAP: conceptualization, data preparation, analysis, and writing—original draft preparation, and writing—review and editing. PFH: funding, conceptualization, data preparation and analysis, writing—original draft preparation, and writing—review and editing; SJP: funding, conceptualization, data preparation, writing—original draft preparation, and writing—review and editing; RBS: conceptualization, data preparation, and writing—review and editing; RWG: conceptualization, data preparation, and writing—review and editing.

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Availability of data and materials
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Declarations

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Not applicable.

Consent for publication
Not applicable.

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

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