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The REBURN model: simulating system-level forest succession and wildfire dynamics

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Abstract

Background Historically, reburn dynamics from cultural and lightning ignitions were central to the ecology of fire in the western United States (wUS), whereby past fire effects limited future fire growth and severity. Over millennia, reburns created heterogenous patchworks of vegetation and fuels that provided avenues and impediments to the flow of future fires, and feedbacks to future fire event sizes and their severity patterns. These dynamics have been significantly altered after more than a century of settler colonization, fire exclusion, and past forest management, now compounded by rapid climatic warming. Under climate change, the area impacted by large and severe wildfires will likely increase — with further implications for self-regulating properties of affected systems. An in-depth understanding of the ecology of reburns and their influence on system-level dynamics provides a baseline for understanding current and future landscape fire-vegetation interactions.

Results Here, we present a detailed characterization of REBURN — a geospatial modeling framework designed to simulate reburn dynamics over large areas and long time frames. We interpret fire-vegetation dynamics for a large testbed landscape in eastern Washington State, USA. The landscape is comprised of common temperate forest and nonforest vegetation types distributed along broad topo-edaphic gradients. Each pixel in a vegetation type is represented by a pathway group (PWG), which assigns a specific state-transition model (STM) based on that pixel's biophysical setting. STMs represent daily simulated and annually summarized vegetation and fuel succession, and wildfire effects on forest and nonforest succession. Wildfire dynamics are driven by annual ignitions, fire weather and topographic conditions, and annual vegetation and fuel successional states of burned and unburned pixels.

Conclusions Our simulation study is the first to evaluate how fire exclusion and forest management altered the active fire regime of this landscape, its surface and canopy fuel patterns, forest and nonforest structural conditions, and the dynamics of forest reburning. The REBURN framework is now being used in related studies to evaluate future climate change scenarios and compare the efficacy of fire and fuel management strategies that either enable the return of active fire regimes or depend on fire suppression and wildfire effects on forest burning.

Keywords Mixed-severity fire, Interior Pacific Northwest, North-central Washington state, Semi-arid forests, Fire and vegetation dynamics, Reburns, Surface and canopy fuel succession, Wildfire dynamics

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Resumen

Antecedentes Históricamente, la dinámica de los fuegos recurrentes iniciados por igniciones tanto culturales como por rayos, fueron eventos centrales en el oeste de los Estados Unidos (wUS), por lo que los efectos de fuegos pasados limitan el crecimiento y severidad de fuegos futuros. A lo largos de milenos, los fuegos recurrentes crearon parches de vegetación y de combustibles heterogéneos que proveyeron de vías e impedimentos en el flujo de fuegos futuros, y retroalimentaciones para eventos de fuegos futuros de diferentes tamaños y sus patrones de severidad. Estas dinámicas fueron significativamente alteradas luego de más de un siglo de colonización por inmigrantes, la exclusión del fuego y el manejo forestal pasado, y ahora intensificadas por el rápido calentamiento global. Bajo el cambio climático, el área impactada por fuegos más grandes y severos probablemente se incremente -con implicaciones para las propiedades de auto-regulación- de los sistemas afectados. Un entendimiento profundo de la ecología de los fuegos recurrentes y su influencia en la dinámica a nivel de sistemas proveerá de una línea de base para entender las interacciones actuales y futuras entre fuegos y vegetación a nivel de paisaje.

Resultados Presentamos acá una detallada caracterización de REBURN, un modelo geoespacial diseñado para simular la dinámica de fuegos recurrentes en grandes áreas y para largos períodos de tiempo. Interpretamos la dinámica fuego-vegetación para un gran banco de prueba a nivel de paisaje en el este del estado de Washington, EEUU. El paisaje está conformado por bosques templados y áreas con tipos de vegetación no boscosa distribuidas a lo largo de amplios gradientes topo-edáficos. Cada pixel en cada tipo de vegetación está representado por un grupo de corredor (PWG), que se asigna a un modelo de transición especifico (STM) basado en los atributos biofísicos de cada pixel. Los STMs representan las simulaciones diarias y resumen anualmente la vegetación y la sucesión del combustible, y los efectos del fuego en áreas boscosas y no boscosas. LA dinámica de los incendios está conducida por las igniciones anuales, las condiciones meteorológicas en relación al fuego y las condiciones de la topografía, y la vegetación anual y los estados sucesionales de los combustibles en pixeles quemados y no quemados.

Conclusiones Nuestro estudio de simulación en el primero en evaluar cómo la exclusión del fuego y el manejo forestal alteraron los regímenes de fuego en este paisaje, los patrones de combustibles superficiales y en los doseles, las condiciones estructurales de las áreas boscosas y no boscosas, y la dinámica de los fuegos recurrentes en esos bosques. La estructura del modelo REBURN está siendo ahora usada en estudios relacionados para evaluar escenarios futuros de cambio climático y comparando la eficacia de estrategias de manejo del fuego y de los combustibles que podría permitir el regreso de regímenes de fuego activos o depender de la supresión y los efectos de los incendios en las quemas forestales.

Background

The area burned by wildfires is increasing around the globe with warmer temperatures, longer fire seasons, and related changes in fire weather (Flannigan et al. 2009; Jolly et al. 2015). Climate projections for western North America (wNA) anticipate a two- to fourfold increase in annual burned area from 2000 to 2050 (Westerling et al. 2011; Abatzoglou et al. 2021). As wildfires burn more forestlands, more area will reburn within prior burn mosaics (Coop et al. 2020). Short-interval (1–2 decades) reburns typically reduce surface and canopy fuels and create fuel discontinuities within previously burned areas (Parks et al. 2012, 2016; McKenzie and Littell 2017). For a time, past fires reduce and decouple surface from canopy fuels in developing forests, making them more difficult to burn at high severities, thereby mitigating the ecological impacts of fire on soils and vegetation (Prichard et al. 2017).

Given that many forests in the fire-prone western US (wUS) have altered fire regimes due to a changing climate (Westerling 2016), surface and canopy fuel accretion through fire exclusion (Hessburg et al. 2019; Hagmann et al. 2021) and increasing human ignitions (Balch et al. 2017), a better understanding is needed regarding the role of forest landscape reburning. Historically, cultural and lightning ignitions made wildfires common and widespread throughout much of the wUS (Marlon et al. 2012; Long et al. 2021). As wildfire returns to wNA landscapes following a long period of fire exclusion, land managers need to know how fire management decisions today can foster more fire and climate-resilient landscapes and human communities in the future (McWethy et al. 2019; Hessburg et al. 2021). Moreover, managers, foresters, and biologists need to better understand how current decisions will impact long-term future trajectories of forest structure, carbon, and wildlife habitat (Falk et al. 2019; Gaines et al. 2022).

Advances in landscape-fire simulation modeling make it possible to simulate long-term interactions among the climate, fire, vegetation, and fuels of an area and the resulting dynamics (Keane et al. 2004; Miller and Davis 2009; Ager et al. 2018). Examples of useful models exist throughout the literature (Cary et al. 2006; Calkin et al. 2011; Spies et al. 2017; Keane et al. 2018; Scheller et al. 2019), and they vary in their simulation approach, focal ecosystems, and applicable geography. A main goal of landscape- and regional-level landscape-fire models is to represent terrestrial and atmospheric processes and interactions that govern climate-fire-vegetation system responses. Once calibrated, models can simulate future successional trajectories, landscape structure and composition, and disturbance interactions under various climate and management scenarios. Scenarios can be used to determine management influences on emergent system properties such as water quality and quantity, wildlife habitat, carbon sequestration, and nutrient cycling. For example, Hurteau et al. (2019) used the process model LANDIS-II (Scheller et al. 2019) to evaluate changes to annual burned area under future climate scenarios. By incorporating fire feedbacks to available fuels, they found a significant reduction in predicted annual burned area and carbon lost to wildfires compared to scenarios where these feedbacks were intentionally removed.

Similarly, landscape-fire modeling simulations have been used to evaluate the influence of fuel reduction or managed wildfire treatments on fire-vegetation dynamics in wNA forests (e.g., Barros et al. 2018; Ager et al. 2020). Informative models are those that balance model complexity (i.e., number of parameters, data resolution, simulation time, number of modeled processes) and model validity (i.e., how close model outputs of interest are to reality, Furniss et al. 2022). For example, a recent model, the Dynamic Temperate and Boreal Fire and Forest-Ecosystem Simulator, was used to evaluate broadscale (1-km resolution) dynamics of fire and vegetation in boreal forests of North America (Hansen et al. 2022). The authors reported reasonable mean fire characteristics over large regions but noted that large fire events under extreme interannual fire weather were difficult to model.

Landscape-fire simulation models require methods for determining the compositional and structural characteristics of vegetation spatially and dynamically over time. Some models, such as LANDIS-II and Fire-BGC, use mechanistic models to represent vegetation conditions and their trajectories over time based on competition for resources, biophysical environments, and disturbances. Alternatively, state-transition models (STMs) are often used to represent vegetation dynamics based on defined parameters for known vegetation trajectories due to succession and disturbance events. STMs discretize the continuous processes of reproduction, growth, and mortality into a defined continuum of states that transition over time based on successional and disturbance-mediated pathways. Both STMs and mechanistic models allow for the inspection of various management pathways to anticipate ecosystem transitions with and without disturbances, and those occurring under alternative management scenarios (Beisner et al. 2003; Bestelmeyer et al. 2009). For example, vegetation and fuel mapping products in LANDFIRE (https://landfire.gov) are used with basic STMs to represent succession and disturbance dynamics across the US (Blankenship et al. 2021). Similarly, iterative simulation modeling that involves climate, fire, and vegetation dynamics makes use of STMs to represent state-transitions associated with vegetation recovery and growth, and interactions with fire over time (Davis et al. 2010; Barros et al. 2017).

Biophysical context and calibration of STMs are important but often overlooked aspects of state-transition modeling (Bestelmeyer et al. 2011). Spatial variation in biogeoclimatic setting and geographic variation in drivers of fire spread and severity are critical factors to realistic simulation of fire-vegetation dynamics (Miller and Ager 2013; Keane et al. 2018). Thus, developing suitable STMs for geospatial application requires that independent validation datasets or modeling that document rates of forest and fuel succession with and without disturbances be used to calibrate dynamics within an STM.

REBURN modeling of vegetation-fire interactions

The REBURN modeling study was motivated by a large wildfire event, the 2006 Tripod Complex, which burned over 70,000 ha after 80 + years without fire. We selected this study area to evaluate the effects of fire exclusion on pre-Tripod-fire landscape vegetation and fuel patterns, to compare fire-excluded and non-fire-excluded conditions, and to better inform large landscape adaptation strategies for future wildland fire management. Following the establishment of the North Cascades Smoke Jumper Base in 1940, which is located just south of the Tripod area, nearly all fire starts were successfully suppressed between 1940 and 2005. Over 300 active ignitions were suppressed within the Tripod perimeter itself, with thousands more in the near vicinity. A previous study of reburn dynamics in the Tripod area demonstrated that although past fire events were rare, they modified subsequent fire spread and severity during the 2006 event (Stevens-Rumann et al. 2016). This observation inspired a set of studies (this paper and Povak et al. 2023) to better understand the role of reburns in future wildfire events and the contributions of past fire suppression to limiting the capacity of a system to regulate the spread and severity of future fire events.

The objectives for developing the REBURN modeling framework in the current application were to (1) evaluate how fire exclusion has contributed to altered vegetation and fuel succession patterns in this temperate forest landscape, and (2) compare future wildland fire management strategies that can safely return an active fire regime to this landscape. In this first study, we evaluated long-term fire and vegetation dynamics to provide context for twentieth-century fire exclusion and examples of frequent fire landscapes. Future work will expand on additional objectives to better understand the influence of altered ignition patterns, Indigenous cultural burning, climate change, and management strategies that can impact reburn dynamics and system-level behavior. Because wildfire is the dominant driver of system-level vegetation dynamics within the Tripod landscape, the vegetation and fuel succession pathways within the REBURN STMs represent how fire events and fire-fire interactions drive forest successional patterns over space and time, set forest and nonforest development on new trajectories, and create a diverse and continually shifting range of forest composition and structural characteristics under the influence of interacting low-, moderate-, and high-severity fire events over space and through time.

This paper documents REBURN model development and calibrated model behavior. We include a full model description, detailed views of STMs, the content of all input landscape files, and ignition and fire weather inputs. We detail our calibration procedures and then present sample REBURN outputs, including representative landscape succession conditions and variation resulting from active fire regimes. A companion paper (Povak et al. 2023) further examines model behavior, evaluating the characteristics of the active fire regimes of each Tripod forest type, and summarizing the effects of forest reburning on system-level dynamics.

Methods

Study area

Our study area is located within north-central Washington State, a region that has experienced a dramatic rise in the incidence and area severely burned by wildfires since the mid-1990s (Fig. 2). The 2006 Tripod Complex burned approximately 70,000 ha of the Okanogan-Wenatchee National Forest, and at the time of the fire, was an exceptional event considering fire size and severity. Two-thirds of the area burned at moderate- and high severity (Prichard and Kennedy 2014). The Tripod study area was selected for this study because STMs could be informed by extensive local field data collection and analysis of burned and unburned areas from prior studies (Prichard and Peterson 2010; Prichard and Kennedy 2014) and reburn dynamics (Stevens-Rumann et al. 2016).

The study area supports a mix of forest vegetation types from low-elevation ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) dry mixed-conifer forests to high-elevation cold mixed-conifer forests of Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and lodgepole pine (*P. contorta*) in pure and mixed conditions. Rugged topographic and aspect differences create marked contrasts between dry sites with high insolation (ridgelines and on south and west aspects), and moist and cool sites (valley bottoms and north and east aspects) with much lower levels and durations of solar exposure. At upper treeline, subalpine parklands of whitebark pine (*Pinus albicaulis*) and subalpine larch (*Larix lyallii*) are present, and the highest elevations are dominated by thin, poorly developed soils, alpine heathlands, and rock. Riparian vegetation represents a minor fraction of the study area (2.3%) and is generally composed of aspen (*Populus trichocarpa*), willow (*Salix* spp.), and deciduous shrubs.

The REBURN modeling framework

The REBURN geospatial modeling framework iteratively models fire-vegetation interactions over time using a wildland fire spread model, STMs, daily fire weather, and probabilistic ignition surfaces (Fig. 1). A base landscape is first developed to represent topography and vegetation conditions. The resolution of these products can vary depending on the REBURN model application. For the Tripod landscape, we used 90-m pixels. Vegetation assignments for pixels are then made by biophysical setting. Four main forest vegetation pathway groups (PWGs) represent biophysical settings in the Tripod landscape: dry mixed-conifer (DMC), moist mixed conifer (MMC), cold-dry conifer (CDC), and cold-moist conifer (CMC) forests. Non-forest PWGs also support non-vegetated conditions (rock, water, ice), edaphic herblands and shrublands, hardwood forests, and alpine meadows (Fig. 2).

Unique STMs are assigned to each PWG, and each pixel is assigned 1 of 40 surface fire behavior fuel models (FBFMs, Scott and Burgan 2005) and a set of canopy fuel parameters needed by the fire growth model (Fig. 1). For every state in each STM, a transition pathway allows for low-, moderate, or high-severity fire to transition that state to any other state as a function of prior burn history and antecedent surface and canopy fuel conditions at the time of ignition. To be tractable, STMs developed here present a realistic yet simplified representation of the continuum of states that could be supported by temporally mixed fire regimes common within our study area. As such, they offer a reasonable means of applying simulated fire behavior and effects on vegetation structure and composition, and then translating wildlife habitat conditions and connectivity, carbon sequestration, or other properties of landscapes with active or inactive fire regimes.

Long-term landscape simulations then proceed as follows. Within a given fire year, fires are modeled within the fire spread model, FSPro, using an ignition location, daily fire weather, and landscape conditions (an LCP file), which includes topographic, canopy fuels, and surface fuel inputs (inner workflow

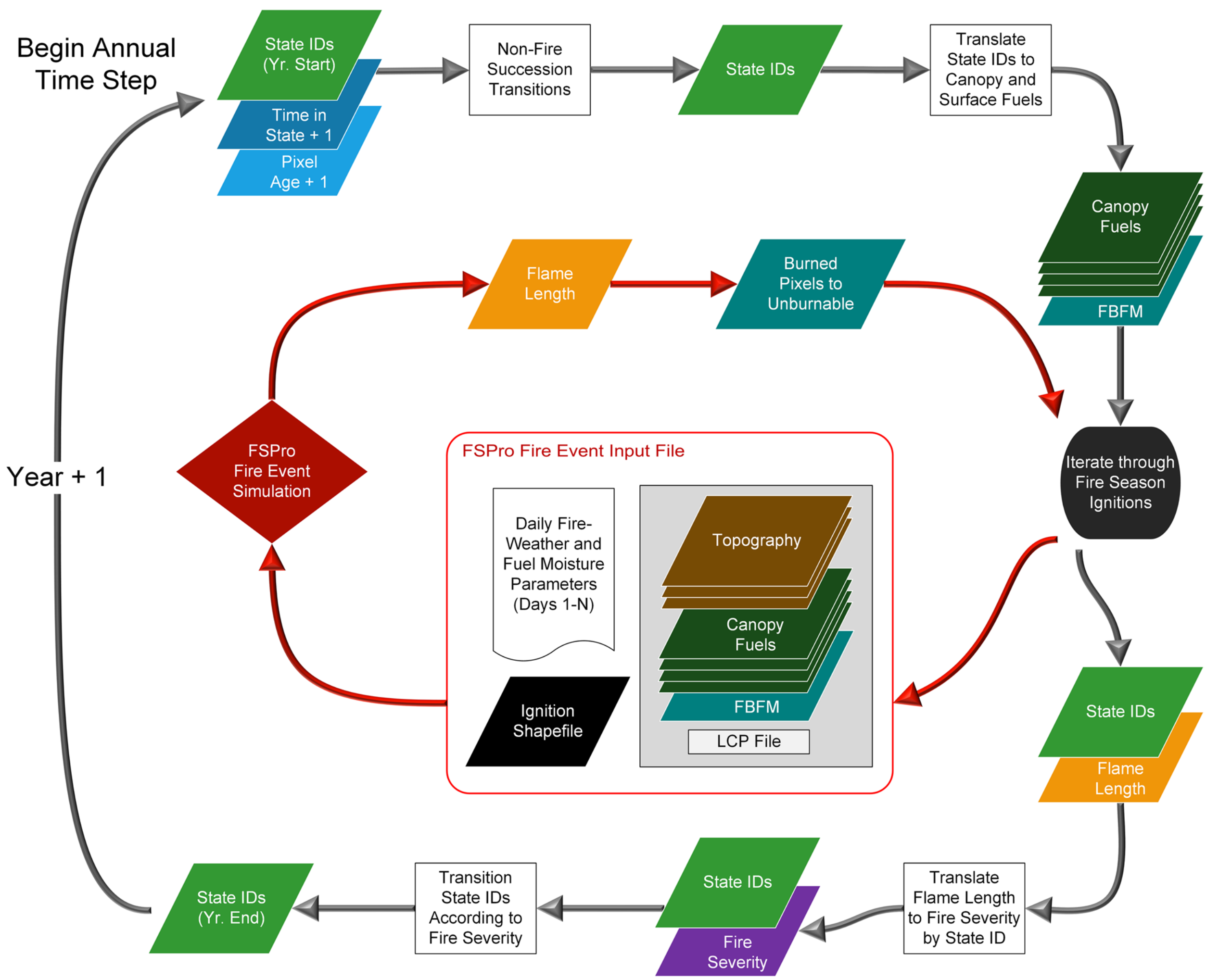

Fig. 1 REBURN workflow diagram. At "*Begin annual time step*," state-transition models (STMs) grow canopy and surface fuels by 1 year (outer workflow). States within STMs are represented by a *State ID*, which is translated to canopy and surface fuel inputs. All ignitions in a given fire year are modeled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

loop Fig. 1) for each 90-m pixel. Burned pixels are then updated to a new State ID using a look-up table that translates predicted flame length to a fire severity class. At the start of every new fire season, a new LCP file is created to account for changes in fuels due to pixels previously burned within the fire season. REBURN outputs include evolving maps of forest vegetation and structural classes, summary statistics of fire size and severity, and the frequency of lethal and non-lethal transitions caused by disturbances and succession. The following sections further describe model inputs, the fire spread model used within the framework, and the full model workflow.

Pathway groups and their unique state-transition models

Pathway group STMs were developed to approximate the complexity of vegetation and fuel conditions within the study area and their interactions with fire. Surface and canopy fuel inputs from these STMs were used to construct fuel layers that are operationally used by several US fire modeling platforms, including FARSITE, FlamMap, Minimum Travel Time, FSPro, and FSIM (Finney 2006; Stratton 2006; Short et al. 2016). Based on field data, site visits, and consultations with area fire managers, we constructed four STMs to represent dry mixed-conifer, moist-mixed conifer, and cold-moist mixed-conifer, and cold-dry mixed-conifer forests that dominated our

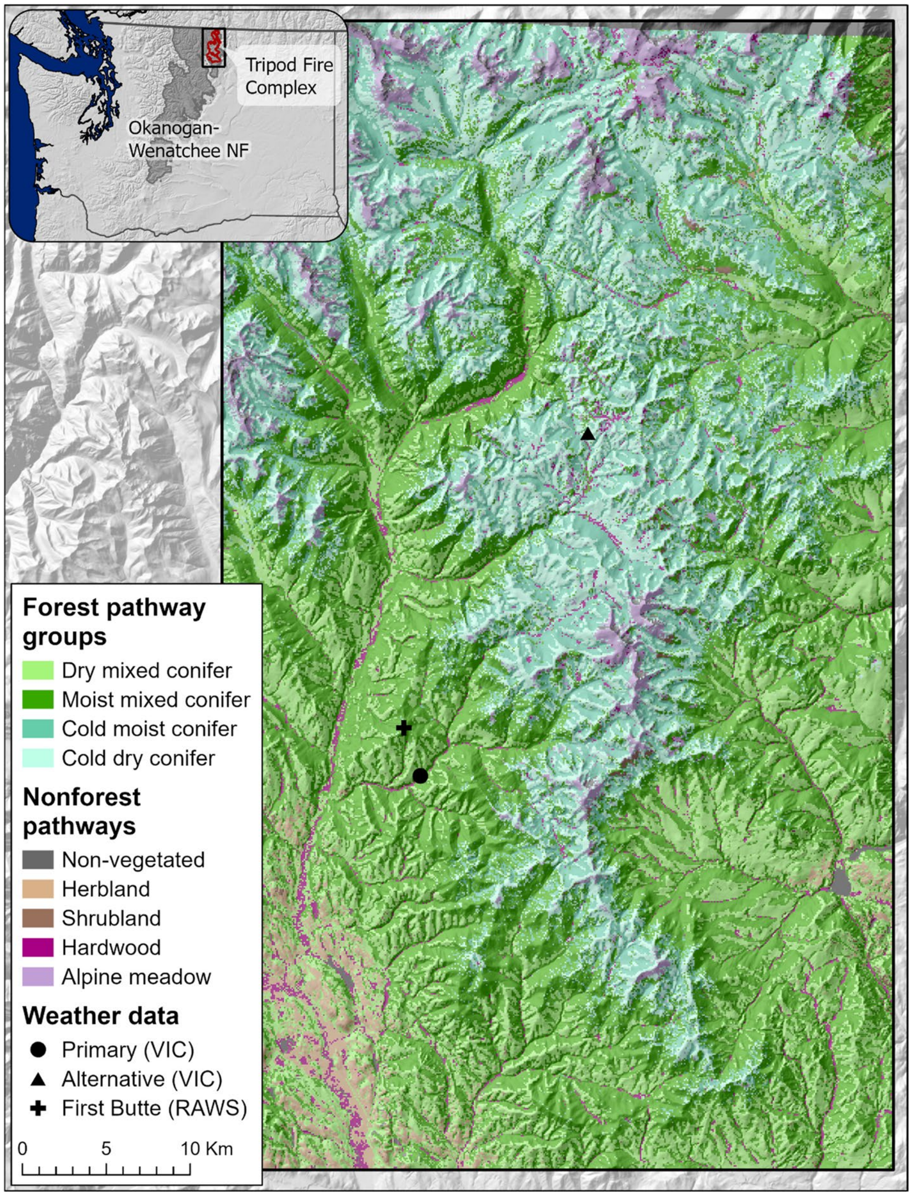

Fig. 2 Vicinity map, study location, and pathway group (PWG) map of the Tripod study area, eastern Washington, USA. Locations of remote area weather stations are indicated by black symbols

study area. Major vegetation PWGs were derived using the LANDFIRE biophysical settings layer (LANDFIRE 2016 Remap; https://landfire.gov/bps.php), aspect, topographic position, and elevation belt maps created by this project (Fig. 2).

The LANDFIRE biophysical settings (https://landfire.gov/bps.php) raster was applied to spatially allocate PWGs to their approximate area. These data represent the broad vegetation types that were likely present prior to Euro-American colonization given biophysical conditions of that time (Rollins 2009). We used the biophysical setting 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 to dry or moist cold mixed-conifer forest conditions. Initial mixed conifer biophysical setting classes were further reclassified to DMC, MMC, CDC, or CMC forest condition based on topographic position, aspect, and elevation belt (Fig. 2). From the biophysical settings dataset, pixels were assigned to a dry PWG variant if they were on a ridgetop, a flat area, or any aspect of the south. Conversely, pixels were assigned

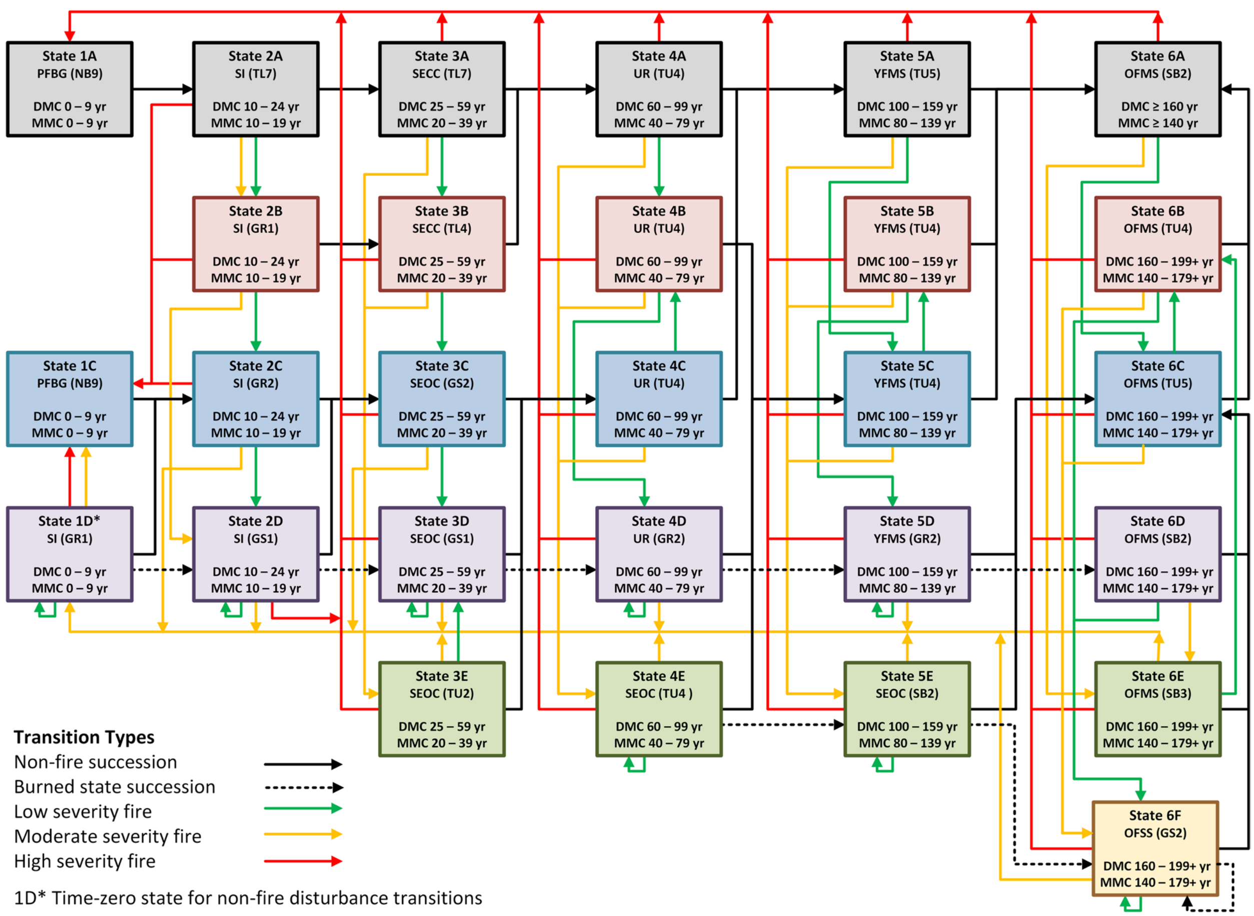

Fig. 3 State-transition model (STM) of dry mixed-conifer (DMC) and moist mixed-conifer (MMC) forests including states with associated structure classes, fire behavior fuel model (FBFM) assignments, and time in state. Transition arrows include non-fire succession (black arrows), succession following low-severity fire within time in state (dotted black line), low-, moderate-, and high-severity fire (green, orange, and red arrows, respectively). Pathways by row: A (fire exclusion), B (low severity), C (high-severity reburn), D (frequent fire), E (moderate severity), and F (savanna)

to a moist PWG variant if they were in a valley-bottom setting or any aspect of the north. Elevational thresholds were applied to the mixed-conifer types to further tease out the transitions in these PWGs. Pixels were assigned to the DMC PWG below 900-m elevation if they were on a north aspect or in a valley-bottom setting, and pixels in DMC PWGs were re-assigned to MMC PWGs if they above 1525-m elevation, regardless of topographic position or aspect, to better show locally verified effects of topography on PWG distribution. The same algorithm was applied to cold forests to differentiate dry and moist sites (CDC/CMC).

Within REBURN, the STMs are used to represent forest successional pathways as vegetation interacts with fire of varied timing and severity (Figs. 3 and 4). Each State ID provides a vegetation structural class (adapted from O'Hara et al. 1996; Hessburg et al. 1999; Tables 1 and 2), a time step between states, and surface and canopy fuel assignments — including a surface fire behavior fuel model (FBFM, Anderson 1982; Scott and Burgan 2005), canopy cover %), canopy base height (m), and canopy bulk density (kg m^{-3}). State assignments and pathways were constructed using a combination of existing datasets and expert judgment derived from field visits to examine fuel complexes before and after the 2006 Tripod fire (Prichard and Peterson 2010; Prichard and Kennedy 2014). Early successional conditions after severe fires and their time in state as barriers to fire spread were informed by past studies of fire-on-fire interactions (Prichard and Kennedy 2014; Stevens-Rumann et al. 2016) and field visits to reburn sites in the study area. Single-state pathways were assigned to barren areas, and edaphic grass and shrub vegetation types that were assumed to rapidly recover to pre-burn conditions after a fire. These pathways included bare ground, grass/herbland, shrubland, riparian hardwood forests, and montane meadows (Table 3). Riparian forests such as aspen and black cottonwood (*P. balsamifera*) represented less than 3% of

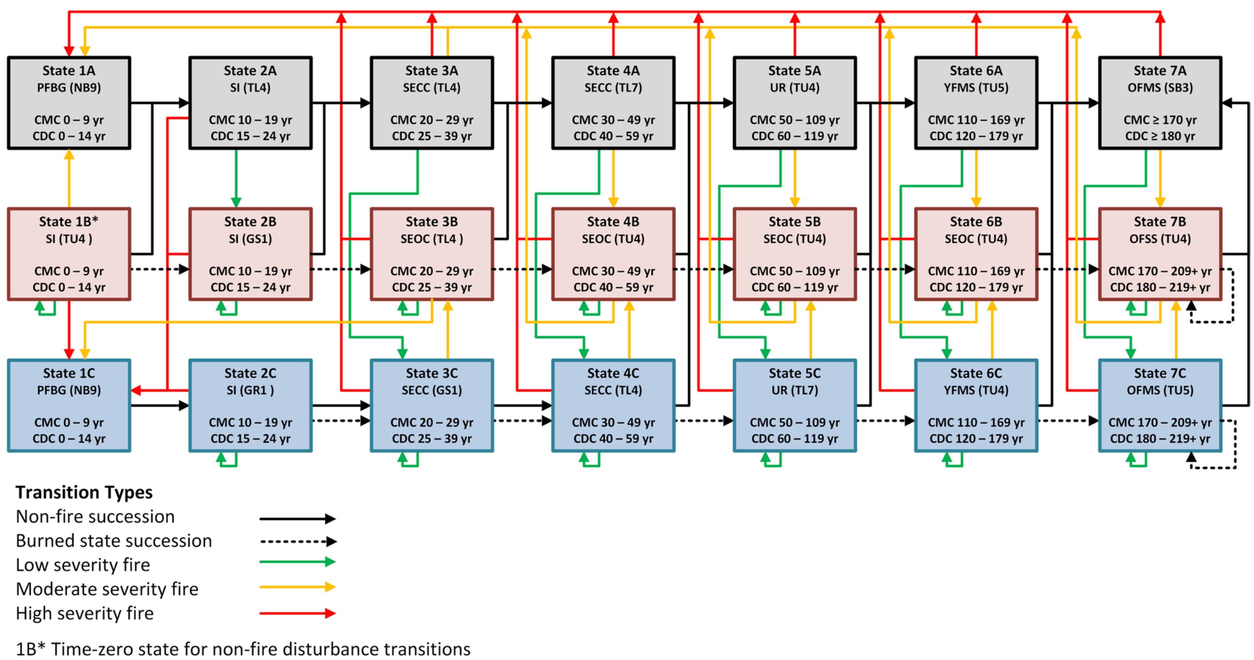

Fig. 4 State-transition (STM) model of cold dry and cold moist mixed-conifer (CDC and CMC) forests including states with associated structure classes, fire behavior fuel model (FBFM) assignments, and time in state. Transition arrows include non-fire succession (black arrows), succession following low-severity fire within time in state (dotted black line), low-, moderate-, and high-severity fire (green, orange, and red arrows, respectively). Pathways by row: A (fire exclusion), B (moderate severity), C (high-severity reburn)

the study area and were also assigned to a single state because they rapidly regenerate to their former conditions from established root systems. However, in future versions of REBURN, these states could be expanded into their respective STMs.

To assign STM successional time steps and canopy and surface fuels, we relied on a combination of field data, independent validation by forest succession and growth modeling with the Forest Vegetation Simulator (FVS, Crookston and Dixon 2005), and expert judgment based on local land manager input and field observations. State transitions for each STM were developed to reflect representative forest development through time after low-, moderate-, or high-severity fire, and the absence of fire. Rates of forest succession in each PWG STM were calibrated within FVS across a range of tree list datasets from FIA plots within the Okanogan Highlands and north Idaho using the Northern Cascades variant of FVS. Simulations included the structural class (keyword StrClass) and canopy fuels (keywords CanCalc, CanFProf) of the Fire and Fuels Extension (FVS-FFE, Rebain 2015). FVS-FFE simulations were run for 250 years and used to validate and inform successional time steps for all STM pathways. For cold mixed-conifer forest (CDC and CMC PWG) STMs dominated by Engelmann spruce, subalpine fir, and lodgepole pine, stand structural class definitions were adjusted to account for potentially lower stocking in stand initiation (changed from a minimum of 494 to 247 trees ha^{-1}), and lower tree diameter (transition diameter threshold was changed from 64 to 38 cm) based on the FVS runs.

Surface and canopy fuel assignments were developed and applied for each state. Canopy fuel assignments were informed by converting a representative range of FIA plots to FVS tree lists (Shaw and Gagnon 2020) and running FVS-FFE simulations over time. FVS-FFE includes surface fuel model assignments as modeled outputs, however, these outputs did not provide realistic assignments for the STMs based on our field observations and those of fire managers in the study area. Similarly, previous work to evaluate the sensitivity of FVS-FFE to fuel treatments found that fire behavior fuel model assignments made by FVS-FFE were limited in their ability to represent surface fuel treatments by fire or management applications (Johnson et al. 2011). Thus, we made assignments based on field observation of state examples (e.g., see Ottmar et al. 2007), field condition comparisons with published fuel photo series (https://depts.washington.edu/nwfire/dps/), and expert judgment from local fire managers.

To represent STM dynamics within fires of spatially mixed severity, we developed pathways and look-up tables to inform state transitions following low-, moderate-, and high-severity fire (Figs. 3 and 4). Transitions

Table 1 Surface and canopy fuel properties of dry mixed conifer (DMC) and moist mixed conifer (MMC) states. *CC* canopy cover (%), *CH* canopy height (m), CBH canopy base height (m), CBD crown bulk density (kg m^{-3}). Stand structural classes include post-fire bare ground (PFBG), stand initiation (SI), stem exclusion open canopy (SEOC), stem exclusion closed canopy (SECC), understory re-initiation (UR), young forest multi-story (YFMS), old forest multi-story (OFMS), and old forest single story (OFSS). Surface fuel models are fire behavior fuel models (FBFMs) of Scott and Burgan (2005). An alternative fuel model assignment (ALT FBFM) is used to represent generally cooler and moister fuels in cold forests

State	Stand structure class	Surface fuel model	ALT FBFM	Dry mixed conifer					Moist mixed conifer				
				Time period (years)	CC (%)	CH (m)	CBH (m)	CBD (kg/m^3)	Time period (years)	CC (%)	CH (m)	CBH (m)	CBD (kg/m^3)
1A	PFBG	NB9	-	0–9	1	2.1	0	0	0–9	1	5	0	0
2A	SI	TL7	-	10–24	40	6	0.5	0.06	10–24	60	9	0.5	0.06
3A	SECC	TL7	-	25–59	80	18	1.5	0.22	20–39	90	19.8	1.5	0.22
4A	UR	TU4	TL7	60–99	70	22	1	0.19	40–79	80	24.2	1	0.19
5A	YFMS	TU5	TU4	100–159	65	31	1	0.18	80–139	75	34.1	1	0.18
6A	OFMS	SB2	TU4	≥ 160	80	35	1	0.22	≥ 140	90	38.5	1	0.22
2B	SI	GR1	-	10–24	30	6	0.7	0.06	10–19	45	8	0.7	0.06
3B	SECC	TL4	-	25–59	68	18	2	0.16	20–39	77	19.8	2	0.16
4B	UR	TU4	TL4	60–99	60	22	1	0.19	40–79	68	22	1	0.19
5B	YFMS	TU4	TL7	100–159	48	31	1.3	0.14	80–139	60	34.1	1.3	0.14
6B	OFMS	TU4	TL7	160–199	64	35	1.5	0.15	140–179	72	38.5	1.5	0.15
1C	PFBG	NB9	-	0–9	1	2	0	0	0–9	1	4	0	0
2C	SI	GR2	-	10–24	25	6.4	1.2	0.06	10–19	38	9	1.2	0.06
3C	SEOC	GS2	-	25–59	54	17	2	0.11	20–39	54	19.8	2	0.11
4C	UR	TU4	-	60–99	60	22	1	0.13	40–79	70	24.2	1	0.13
5C	YFMS	TU4	-	100–159	65	31	1	0.12	80–139	75	34.1	1	0.12
6C	OFMS	TU5	TL7	160–199	75	35	1	0.16	140–179	85	38.5	1	0.16
1D	SI	GR1	-	0–9	1	2	0	0	0–9	1	4	0	0
2D	SI	GS1	-	10–24	19	6	1.5	0.04	10–19	34	9	1.5	0.04
3D	SEOC	GS1	-	25–59	43	18	2.3	0.1	20–39	61	19.8	2.3	0.1
4D	UR	GR2	-	60–99	48	22	1	0.11	40–79	54	23.1	1.5	0.11
5D	YFMS	GR2	-	100–159	50	31	1.5	0.1	80–139	57	35.2	1.5	0.1
6D	OFMS	SB2	-	160–199	52	35	1.5	0.12	140–179	68	38.5	1.5	0.12
3E	SEOC	TU2	-	25–59	34	18	2.5	0.07	20–39	21	19.8	2.5	0.07
4E	SEOC	TU4	-	60–99	38	22	2	0.09	40–79	41	23.1	2	0.09
5E	SEOC	SB2	-	100–159	40	31	2	0.09	80–139	50	35.2	2	0.09
6E	OFSS	SB3	-	160–200	42	35	1.5	0.09	140–179	60	38.5	1.5	0.09
6F	OFSS	GS2	-	160–199	33	35	2	0.06	140–179	48	38.5	2	0.06

Table 2 Surface and canopy fuel properties of dry mixed conifer (DMC) and moist mixed conifer (MMC) states. *CC* canopy cover (%), *CH* canopy height (m), CBH canopy base height (m), CBD crown bulk density (kg m^{-3}). Stand structural classes include post-fire bare ground (PFBG), stand initiation (SI), stem exclusion open canopy (SEOC), stem exclusion closed canopy (SECC), understory re-initiation (UR), young forest multi-story (YFMS), old forest multi-story (OFMS), and old forest single story (OFSS). Surface fuel models are fire behavior fuel models (FBFMs) of Scott and Burgan (2005). An alternative fuel model assignment (ALT FBFM) is used to represent generally cooler and moister fuels in cold forests

State	Stand structure class	Surface fuel model	ALT FBFM	Cold Dry Conifer					Cold Moist Conifer				
				Time period (years)	CC (%)	CH (m)	CBH (m)	CBD (kg/m^3)	Time period (years)	CC (%)	CH (m)	CBH (m)	CBD (kg/m^3)
1A	PFBG	NB9	-	0–14	14	2	0	0	0–9	14	2	0	0
2A	SI	TL4	-	15–24	43	7.6	0.2	0.12	10–19	43	8.4	0.2	0.12
3A	SECC	TL4	-	25–39	75	15.2	0.5	0.22	20–29	75	16.8	0.5	0.22
4A	SECC	TL7		40–59	80	18.3	0.5	0.3	30–49	85	20.1	0.5	0.3
5A	UR	TU4	TL4	60–119	90	24.4	1.2	0.3	50–109	86	26.8	0.7	0.22
6A	YFMS	TU5	TL4	120–179	95	25	1.2	0.31	110–169	90	27.5	0.7	0.31
7A	OFMS	SB3	TL4	≥ 180	85	27.4	1.2	0.31	≥ 170	94	30.2	0.7	0.31
1B	SI	TU4	SB1	0–14	14	2	0	0	0–9	14	2	0	0
2B	SI	GS1	TL4	15–24	26	7.6	0.3	0.06	10–19	34	8.4	0.3	0.09
3B	SEOC	TL4		25–39	45	15.2	0.5	0.08	20–29	45	16.8	0.5	0.08
4B	SEOC	TU4	TL4	40–59	48	18.3	0.3	0.09	30–49	60	20.1	0.3	0.11
5B	SEOC	TU4	TL4	60–119	54	24.4	0.5	0.11	50–109	60	26.8	0.5	0.12
6B	SEOC	TU4	TL4	120–179	57	25	0.5	0.12	110–169	63	27.5	0.5	0.13
7B	OFSS	TU4	TL4	180–219	51	27.4	1.2	0.1	170–209	66	30.2	1.2	0.14
1C	PFBG	NB9	-	0–14	7	2	0	0	0–9	7	2	0	0
2C	SI	GR1	TL4	15–24	30	7.6	0.3	0.09	10–19	30	8.4	0.3	0.09
3C	SEOC	GS1	TL4	25–39	55	15.2	0.5	0.16	20–29	65	16.8	0.5	0.16
4C	UR	TL4		40–59	70	18.3	0.5	0.22	30–49	75	20.1	0.5	0.2
5C	UR	TL7	TL4	60–119	85	24.4	1.2	0.28	50–109	79	26.8	0.7	0.21
6C	YFMS	TU4	TL4	120–179	90	25	1.2	0.31	110–169	86	27.5	0.7	0.22
7C	OFMS	TU5	TL4	180–219	85	27.4	1.2	0.31	170–209	93	30.2	0.7	0.31

Table 3 Surface and canopy fuel properties of states that are not within a STM pathway and are represented by static states. *CC* canopy cover (%), *CH* canopy height (m), *CBH* canopy base height (m), *CBD* crown bulk density (kg m^{-3})

State	Stand structure class	Surface fuel model	Alt fuel model	Time period (years)	CC (%)	CH (m)	CBH (m)	CBD (kg/m^3)
1A	Barren (rock, water, ice)	NB9	-	-	0	0	0	0
1B	Grassland/herbland	GR4	-	-	0	0	0	0
1C	Shrubland	GS2	-	-	0	0	0	0
1D	Hardwood forest	TL2	TU1	-	60	15	5	0.13
1E	Montane meadow	TU1	-	-	0	0	0	0

were informed by predicted flame lengths derived from FSPro fire behavior simulations (Additional Tables S1 and S2). For each state within the STMs, we identified a representative tree species or species mix (e.g., ponderosa pine and Douglas-fir in DMC forests, western larch and Douglas-fir in MMC forests, and lodgepole pine with subalpine fir and Engelmann spruce in CDC and CMC forests). We then used FOFEM version 6.7 (Lutes 2020) to evaluate predicted tree mortality across a range of input flame lengths that would inform a model look-up table for predicted flame length of low-, moderate-, and high-severity disturbances to each state within each STM (Tables 4 and 5).

In addition to the FBFM assignments required for fire behavior modeling, we constructed fuelbeds to represent each state within the Fuel Characteristics Classification System (FCCS, Ottmar et al. 2007). The FCCS catalogs and classifies fuelbed attributes by stratum (e.g., canopy, shrub, herbaceous, downed wood, litter-lichen-moss, and ground fuels), and fuel categories by stratum (e.g., trees, snags, and ladder fuels for canopy layers and sound and rotten wood, stumps and piles for downed wood). Fuelbeds were customized based on reference datasets within FCCS that represent the major vegetation types, including low-elevation mixed-conifer dominated by Douglas-fir and ponderosa pine, mid-elevation forest represented by mixes of western larch (*Larix occidentalis*), Douglas-fir, and lodgepole pine, and higher elevation Engelmann spruce-subalpine fire-lodgepole pine cold forests. Additional reference datasets included natural fuels photo series (without harvest, Ottmar et al. 1998), activity fuel photo series (with harvest, Fisher 1981a, b), and field datasets (Prichard and Peterson 2010; Stevens-Rumann et al. 2016). FCCS fuelbeds were informed by reference data but also relied on expert judgment for the time period of transitions of canopy and surface fuel characteristics between states and pathways along ramp functions. A total of 103 fuelbeds were constructed to represent each state within the four PWG STMs (Additional Files S3) and five non-forest state fuelbeds representing bare ground, grassland/herbland, shrubland, riparian hardwood forests, and montane meadows. FCCS fuelbeds contained the same canopy fuel inputs as were used in the inputs to FSPro and were calibrated to similar surface fuel conditions (i.e., live shrubs, herbs, fine wood, and litter) and predicted rates of spread and flame lengths based on comparative calculations of surface fire behavior in FCCS and BehavePlus.

Fire growth model

The fire growth model, FSPro (Calkin et al. 2011), was selected to simulate wildfire spread, fireline intensity, and flame length given ignition locations, daily weather streams and fuel moisture data, canopy and surface fuel conditions, and topography. FSPro is ordinarily used as a probabilistic model to predict fire growth across landscapes (Finney et al. 2011). Fires are simulated using the Minimum Travel Time (MTT; Finney 2002) algorithm, which models fire spread from an ignition location across a gridded lattice by identifying the nodes (pixel corners) on a fire's travel route with the fastest spread rate paths (i.e., shortest travel times). This algorithm has been shown to recreate realistic fire growth patterns, spread rates, and flame lengths (Finney 2002; Finney et al. 2011).

FSPro was selected for this study because it allowed for (1) variable daily energy release component values (ERC, Bradshaw et al. 1983), wind speed, and wind direction assignment by burn period; (2) specification of ERC thresholds to burning that could be used to predetermine fuel moistures and the length of each burn period; and (3) use of a command-line version that can be integrated into an ArcGISPro geospatial modeling workflow. FSPro is used within the Wildland Fire Decision Support System by fire managers for strategic and tactical management decision-making (Taber et al. 2013) during actual wildfire incidents to predict the future probability of burning of an affected landscape. In such instances, the model is often run over thousands of iterations under various predicted wind and weather streams drawn from historical weather data supplied by the user. Our process incorporated known daily weather data, precluding the

Table 4 Flame length (m) transitions to fire severity for states within dry mixed conifer (DMC) and moist mixed conifer (MMC) pathways

State ID	Pathway group	State	Very low	Low	Mod	High
1211	DMC	1A	-	-	-	-
1212	DMC	2A	< 0.25	≤ 0.73	≤ 1.01	> 1.01
1213	DMC	3A	< 0.25	≤ 1.46	≤ 2.04	> 2.04
1214	DMC	4A	< 0.25	≤ 1.58	≤ 2.38	> 2.38
1215	DMC	5A	< 0.25	≤ 2.01	≤ 2.96	> 2.96
1216	DMC	6A	< 0.25	≤ 2.19	≤ 3.23	> 3.23
1222	DMC	2B	< 0.25	≤ 0.70	≤ 0.98	> 0.98
1223	DMC	3B	< 0.25	≤ 1.49	≤ 2.04	> 2.04
1224	DMC	4B	< 0.25	≤ 1.71	≤ 2.38	> 2.38
1225	DMC	5B	< 0.25	≤ 2.01	≤ 2.99	> 2.99
1226	DMC	6B	< 0.25	≤ 2.35	≤ 3.26	> 3.26
1231	DMC	1C	-	-	-	-
1232	DMC	2C	< 0.25	≤ 0.64	≤ 0.82	> 0.82
1233	DMC	3C	< 0.25	≤ 1.43	≤ 1.98	> 1.98
1234	DMC	4C	< 0.25	≤ 1.58	≤ 2.38	> 2.38
1235	DMC	5C	< 0.25	≤ 2.01	≤ 2.96	> 2.96
1236	DMC	6C	< 0.25	≤ 2.19	≤ 3.20	> 3.20
1241	DMC	1D	< 0.08	≤ 0.30	≤ 0.46	> 0.46
1242	DMC	2D	< 0.25	≤ 0.73	≤ 1.01	> 1.01
1243	DMC	3D	< 0.25	≤ 1.58	≤ 2.07	> 2.07
1244	DMC	4D	< 0.25	≤ 1.71	≤ 2.38	> 2.38
1245	DMC	5D	< 0.25	≤ 2.16	≤ 3.02	> 3.02
1246	DMC	6D	< 0.25	≤ 2.32	≤ 3.26	> 3.26
1253	DMC	3E	< 0.25	≤ 1.58	≤ 2.07	> 2.07
1254	DMC	4E	< 0.25	≤ 1.71	≤ 2.38	> 2.38
1255	DMC	5E	< 0.25	≤ 2.16	≤ 3.02	> 3.02
1256	DMC	6E	< 0.25	≤ 2.35	≤ 3.26	> 3.26
1266	DMC	6F	< 0.25	≤ 2.35	≤ 3.26	> 3.26
1311	MMC	1A	-	-	-	-
1312	MMC	2A	< 0.25	≤ 0.61	≤ 0.85	> 0.85
1313	MMC	3A	< 0.25	≤ 1.58	≤ 2.19	> 2.19
1314	MMC	4A	< 0.25	≤ 1.71	≤ 2.50	> 2.50
1315	MMC	5A	< 0.25	≤ 2.13	≤ 3.17	> 3.17
1316	MMC	6A	< 0.25	≤ 2.32	≤ 3.41	> 3.41
1322	MMC	2B	< 0.25	≤ 0.67	≤ 0.85	> 0.85
1323	MMC	3B	< 0.25	≤ 1.58	≤ 2.19	> 2.19
1324	MMC	4B	< 0.25	≤ 1.71	≤ 2.35	> 2.35
1325	MMC	5B	< 0.25	≤ 2.13	≤ 3.17	> 3.17
1326	MMC	6B	< 0.25	≤ 2.50	≤ 3.47	> 3.47
1331	MMC	1C	-	-	-	-
1332	MMC	2C	< 0.25	≤ 0.67	≤ 0.85	> 0.85
1333	MMC	3C	< 0.25	≤ 1.68	≤ 2.19	> 2.19
1334	MMC	4C	< 0.25	≤ 1.71	≤ 2.50	> 2.50
1335	MMC	5C	< 0.25	≤ 2.13	≤ 3.17	> 3.17
1336	MMC	6C	< 0.25	≤ 2.32	≤ 3.41	> 3.41
1341	MMC	1D	< 0.08	≤ 0.24	≤ 0.40	> 0.40
1342	MMC	2D	< 0.25	≤ 0.67	≤ 0.85	> 0.85
1343	MMC	3D	< 0.25	≤ 1.68	≤ 2.19	> 2.19

Table 4 (continued)

State ID	Pathway group	State	Very low	Low	Mod	High
1344	MMC	4D	< 0.25	≤ 1.77	≤ 2.44	> 2.44
1345	MMC	5D	< 0.25	≤ 2.35	≤ 3.26	> 3.26
1346	MMC	6D	< 0.25	≤ 2.32	≤ 3.44	> 3.44
1353	MMC	3E	< 0.25	≤ 1.68	≤ 2.23	> 2.23
1354	MMC	4E	< 0.25	≤ 1.77	≤ 2.44	> 2.44
1355	MMC	5E	< 0.25	≤ 2.35	≤ 3.26	> 3.26
1356	MMC	6E	< 0.25	≤ 2.50	≤ 3.44	> 3.44
1366	MMC	6F	< 0.25	≤ 2.32	≤ 3.44	> 3.44

need to predict the weather. Thus, we specified wind and weather conditions in FSPro for each ignition.

Ignitions

Ignition locations were drawn from a lightning ignition probability surface that we developed using historical lightning strike point data (National Lightning Detection Network 1990–2010, Cummins and Murphy 2009), with strikes constrained within a nominal fire season for eastern Washington (March 31 through October 26). The annual ignition count was determined by random draw from a distribution of fire starts derived from the Pacific Northwest Region 6, Fire History Wildfire Points of Origin dataset (USDA Forest Service 2014). This dataset contained reliable point location and year of fire data for the period 1940–2013 but lacked fire start date and cause of fire information for a portion of the record. To fire address this discrepancy, we assigned a Julian start date for each fire by random draw from a probability density function developed from an historical wildfire occurrence dataset (Short et al. 2016). When an ignition day was drawn with an ERC value below the minimum FSPro defined value for a growth day (< 55), the Julian date was redrawn to ensure fire ignition and subsequent spread.

Weather data

FSPro anticipates receiving a time series of daily ERC, wind speed and direction values, and fuel moistures for each successfully ignited fire event. Fuel moisture values include data on daily 1-, 10-, 100-h dead fuel moisture time lags (Brown 1974), live herbaceous and live woody fuel moistures, daily burn period (minutes), and spotting probability. For model calibration, we used historical daily weather data from the VIC (Variable Infiltration Capacity) model (Livneh et al. 2013). This dataset was selected because it spanned the temporal record of our wildfire ignition database, covered a sufficiently broad geographic extent, and was spatially gridded, which enabled selection from many individual VIC "virtual weather station" locations within the study area. Variables included 3-h time steps for precipitation, temperature, relative humidity, solar radiation, and wind speed for the years 1915–2011. Weather streams were derived from over 20,000 NOAA Cooperative Observer stations at a spatial resolution of 1/16th degrees latitude/longitude. 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. We also selected a VIC grid point within the high-elevation cold forest zone to provide additional insight into weather variation across the elevational gradient of the study area (Fig. 2). From these data we constructed a FW13 file — a common weather observation data transfer format — and then submitted the VIC weather data to FireFamily Plus (Bradshaw and McCormick 2000) to calculate the daily ERC values.

Fuel moisture bins were calculated for fires that ignited during the spring, summer, and autumn seasons (Table 6). This allowed for temporal variation in the percentile fuel moistures and burn period lengths across a year. For each season, a time series of ERC values estimated at 1300 h each day was created from 1940 to 2006, and fuel moistures were calculated as the average fuel moisture at each time-lag, for each percentile ERC bin.

Wind direction and speed data were derived from the First Butte RAWS (Remote Automated Weather Station) station from 1998 to 2015 and included winds recorded between 1000 and 2000 h from July 1 to September 30 (Table 7). A wind frequency matrix was created from these data, which provided frequencies of specific wind speed and direction combinations. This matrix was then used to draw daily wind speeds and directions for each day of each fire event.

REBURN model workflow

For the REBURN modeling framework, we developed an integrated GIS workflow that simulated: (1) pre-season vegetation growth and fuel accumulation via successional transitions after incrementing pixel age by one annual timestep; (2) the fire season by iterating through individual fire events, where each day within a fire event

Table 5 Flame length (m) transitions to fire severity for states within cold dry conifer (CDC) and cold moist conifer (CMC) pathways

State ID	Pathway group	State	Very low	Low	Mod	High
1511	CDC	1A	-	-	-	-
1512	CDC	2A	< 0.08	≤ 0.30	≤ 0.30	> 0.30
1513	CDC	3A	< 0.08	≤ 0.30	≤ 1.22	> 1.22
1514	CDC	4A	< 0.08	≤ 0.43	≤ 1.40	> 1.40
1515	CDC	5A	< 0.08	≤ 0.61	≤ 1.83	> 1.83
1516	CDC	6A	< 0.08	≤ 0.79	≤ 2.41	> 2.41
1517	CDC	7A	< 0.08	≤ 0.85	≤ 2.53	> 2.53
1521	CDC	2B	< 0.08	≤ 0.30	≤ 1.22	> 1.22
1522	CDC	3B	< 0.08	≤ 0.30	≤ 0.30	> 0.30
1523	CDC	4B	< 0.08	≤ 0.30	≤ 1.22	> 1.22
1524	CDC	5B	< 0.08	≤ 0.43	≤ 1.40	> 1.40
1525	CDC	6B	< 0.08	≤ 0.61	≤ 1.83	> 1.83
1526	CDC	6B	< 0.08	≤ 0.79	≤ 2.41	> 2.41
1527	CDC	7B	< 0.08	≤ 0.79	≤ 2.53	> 2.53
1531	CDC	1C	-	-	-	-
1532	CDC	2C	< 0.08	≤ 0.30	≤ 0.30	> 0.30
1533	CDC	3C	< 0.08	≤ 0.30	≤ 1.22	> 1.22
1534	CDC	4C	< 0.08	≤ 0.43	≤ 1.40	> 1.40
1535	CDC	5C	< 0.08	≤ 0.61	≤ 1.83	> 1.83
1536	CDC	6C	< 0.08	≤ 0.79	≤ 2.41	> 2.41
1537	CDC	7C	< 0.08	≤ 0.85	≤ 2.53	> 2.53
1511	CMC	1A	-	-	-	-
1512	CMC	2A	< 0.08	≤ 0.30	≤ 0.30	> 0.30
1513	CMC	3A	< 0.08	≤ 0.40	≤ 1.31	> 1.31
1514	CMC	4A	< 0.08	≤ 0.49	≤ 1.52	> 1.52
1515	CMC	5A	< 0.08	≤ 0.64	≤ 1.95	> 1.95
1516	CMC	6A	< 0.08	≤ 0.64	≤ 1.98	> 1.98
1517	CMC	6A	< 0.08	≤ 0.70	≤ 2.13	> 2.13
1521	CMC	2B	< 0.08	≤ 0.40	≤ 1.31	> 1.31
1522	CMC	3B	< 0.08	≤ 0.30	≤ 0.30	> 0.30
1523	CMC	4B	< 0.08	≤ 0.40	≤ 1.31	> 1.31
1524	CMC	5B	< 0.08	≤ 0.49	≤ 1.52	> 1.52
1525	CMC	6B	< 0.08	≤ 0.64	≤ 1.95	> 1.95
1526	CMC	6B	< 0.08	≤ 0.64	≤ 1.98	> 1.98
1527	CMC	6B	< 0.08	≤ 0.70	≤ 2.13	> 2.13
1531	CMC	1C	-	-	-	-
1532	CMC	2C	< 0.08	≤ 0.30	≤ 0.30	> 0.30
1533	CMC	3C	< 0.08	≤ 0.40	≤ 1.31	> 1.31
1534	CMC	4C	< 0.08	≤ 0.49	≤ 1.55	> 1.55
1535	CMC	5C	< 0.08	≤ 0.64	≤ 1.92	> 1.92
1536	CMC	6C	< 0.08	≤ 0.64	≤ 1.98	> 1.98
1537	CMC	7C	< 0.08	≤ 0.70	≤ 2.13	> 2.13

received a unique ignition location, daily ERC, wind, and fuel moisture parameters; and (3) post-season vegetation state transitions for each burned pixel according to the pre-burned state's flame length to fire severity translation (see Fig. 1 workflow).

Year start (begin annual time-step)

At the beginning of each annual time-step, we added 1 year to all pixels within the *time in state* (years since the current state assignment), *pixel age* (years since the last high severity disturbance), and *time since burn* (years

Table 6 Within-season average fuel moistures calculated across percentile ERC bins for the 2006 Tripod study area. Seasons include Spring (March 31–May 31), Summer (June 1–September 15), and Autumn (September 16–November 1). ERC is the energy release component; 1, 10, and 100 h are dead fuel moistures for their respective time lag fuel classes; *H* herbaceous fuel moisture; *W* woody fuel moisture and BP is daily burn period in minutes

Season	ERC Percentiles	ERC min	ERC max	1 h	10 h	100 h	H	W	BP
Spring	60–75	43	53	11	12	11	150	200	240
	75–85	53	61	7	8	9	150	200	240
	85–95	61	74	6	7	8	150	200	240
	95–100	74	97	4	5	6	150	200	240
Summer	60–75	55	69	8	9	9	70	100	240
	75–85	69	76	6	7	7	70	100	300
	85–95	76	85	4	5	6	70	90	360
	95–100	85	100	3	3	5	50	80	420
Autumn	60–75	46	58	10	11	11	70	110	300
	75–85	58	66	7	7	9	70	110	300
	85–95	66	76	4	5	7	70	110	300
	95–100	76	92	3	4	6	70	110	300

Table 7 Weighted wind matrix for the First Butte RAWS station used to approximate frequency of wind direction and speed combinations. The calm weight value (0 km per hour, kph) was 5.58

kph	Aspect							
	N (360°)	NE (45°)	E (90°)	SE (135°)	S (180°)	SW (225°)	W (270°)	NW (315°)
8.0	1.82	1.42	1.78	2.88	11.45	11.51	5.87	3.10
16.1	0.99	0.41	0.97	2.31	9.17	6.41	3.88	4.21
24.1	0.75	0.20	0.49	1.31	6.25	4.99	2.66	3.21
32.2	0.34	0.04	0.17	0.41	1.41	0.80	0.61	1.14
40.2	0.13	0.01	0.04	0.08	0.23	0.09	0.09	0.40
48.3	0.04	0.01	0.00	0.03	0.03	0.01	0.03	0.15
56.3	0.02	0.00	0.00	0.01	0.01	0.01	0.00	0.03
64.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01

since the last fire of any severity) rasters. Successional transitions were then executed by means of a sequence of spatial queries in ArcGIS to update the State ID raster. Similarly, non-fire lethal conditions were queried for each annual time step, and where true, the State ID raster was updated and the *time in state* and *pixel age* rasters were reset to zero.

Before each new fire season, we regenerated the initial spatial fuel layers (i.e., the LCP file) used by FSPro. Specifically, canopy fuel rasters were regenerated (canopy cover, crown height, crown base height, and canopy bulk density) by translating the State ID raster initial values from a lookup table (Tables 1 and 2). Values were then adjusted to compensate for within-state annual growth by applying a linear ramp function between the state's initial value and that of the next successional state based on the pixel's age relative the end member values defining the ramp.

We generated the surface fuel layers (FBFMs) by direct translation from the State ID raster (Fig. 1). The Scott and Burgan (2005) 40 FBFMs comprise a set of fuelbed inputs needed by a particular fire behavior or fire effects model. While different kinds of fuel inputs are used in fire modeling, FBFMs are stylized models specifically designed for use with the Rothermel (1972) surface fire spread model, which is employed by FSPro. Within the REBURN modeling framework, surface fuels are converted to a non-burnable fuel model (NB9) if they have recently burned at less than high-severity. This adjustment is made to reflect the temporary reduction of surface fuels in response to low or moderate fire severity. The period of this reduction (in years) was designated by PWG (herbland = 0 years; shrubland, hardwood, alpine meadow = 5 years; DMC = 5 years, MMC = 5 years; CMC = 5 years; and CDC = 10 years) and assigned based on the length of time a past fire was expected to remain a barrier to fire flow (Prichard and Peterson 2010; Prichard and Kennedy 2014; Stevens-Rumann et al. 2016).

Prior to the start of the fire season, the annual ignition count was drawn from the previously described probability density function, and the spatial ignition locations were drawn from the lightning ignition probability surface for each fire (see the "Ignitions" section above). No fire occurred if the ignition location intersected a non-burnable fuel model within a burnable PWG (i.e., no ignition in the ignition accounting). Doing so captured the *fences* and *corridors* (sensu Moritz et al. 2011) provided by recently consumed and recovering fuel patterns over the simulation timeline, respectively. To assign a fire start date, duration, and daily weather, we selected a year from the historical weather record (1940–2005) by random uniform draw to provide the weather stream for the entire fire season. For each fire, an ignition date was then assigned to a fire by drawing from the Julian start date distribution (see the "Ignitions" section above). Fire event duration and daily weather parameters were subsequently assigned by querying the fire start date and the selected annual weather stream. The event duration was determined by querying the daily ERC values, starting with the ignition date, and accumulating days until one of two conditions were satisfied: (1) the weather stream provided two consecutive days below the minimum daily fire growth ERC (<55), or (2) the event duration reached a maximum of 14 days (see the "Model calibration" section below).

Fire season

Within the modeling workflow, fire seasons progressed by iteratively modeling fire events in order of ignition date. The command line version of the fire model FSPro requires a new input parameter file for each simulation with an event specific ignition shapefile, daily ERC, wind speed and direction, fuel moisture values, and burn period (minutes). Daily fuel moisture values were selected using a two-stage lookup (see the "Weather data" section, Table 6), where seasonality was selected by the burn date, and fuel moistures were selected by comparing the daily ERC value to the ERC percentile bins. The FSPro input file also required access to a LCP file, which is a multiband spatial file (90-m resolution) containing the topographic rasters (elevation (m), aspect, and slope %), the canopy fuel rasters generated prior to the fire season, and a surface fuel (FBFM) raster.

FSPro, in the present version, is unable to condition fuel moistures based on fuel model, elevation, or aspect conditions. To account for spatial differences in seasonal fuel moistures between low- and high-elevation pixels, we provided one of two fire behavior fuel model rasters, an FBFM or Alt_FBFM, to the LCP file. The Alt_FBFM raster provided states within the cold mixed-conifer forest zones (CMC and CDC) with FBFMs that burn at lower flame length and spread rates to retard fire growth consistent with higher expected fuel moistures. Our study area contained steep aspect and elevation gradients. To mitigate the simplifying effect of providing fuel moistures based solely on ERC values from one primary low-elevation weather stream location (at 935 m elevation), we queried the ERC values of a second VIC virtual weather station located within the cold conifer PWG area at 1895-m elevation (Fig. 2). If any day within the fire event recorded an ERC that met the minimum criteria for a fire growth day (i.e., ERC ≥ 55) within the VIC weather location's weather stream, then the primary FBFM raster was incorporated into the LCP file. Otherwise, the Alt_FBFM raster was used (Tables 1, 2, and 3). Fuel model layers were updated at the conclusion of each fire event to convert all burned pixels to non-burnable (NB9) conditions (Figs. 3 and 4) for the duration of the fire season and to prevent reburning of already burned pixels within the same fire season. To allow for this update, the LCP file was regenerated prior to each fire event simulation. At the conclusion of each fire event simulation, the flame lengths of all burned pixels were added to a cumulative fire season flame length raster.

Year end

After the last fire event simulation had finished, the fire season flame length raster was processed to convert flame length to fire severity class (Tables 4 and 5). Every unique state that burned within the fire season was classified to one of four fire severity classes (very-low, low, moderate, or high). Pixels of a single state could be classified to any of the four severity classes based on the FSPro flame length output for each cell in the lattice. Finally, the burned pixels were transitioned to the post-burn state values based on the resulting fire severity class.

Model calibration

To calibrate the REBURN model, we ran multiple simulations and saved spatial outputs on a 5-year increment. Calibration simulations were begun with all pixels assigned to PWG-specific state 1A (NB9, post-fire bare ground). Calibration runs proceeded for 1000–1500 years, after a 300-year spin-up period that allowed patterns of succession and wildfire dynamics to fully develop. Output raster layers included maps of State IDs, which then could be cross-walked to structural class, forest age, and FCCS fuelbed conditions. Modeled ignitions and fire weather were based on historical lightning ignition and weather datasets to better understand the effects of fire exclusion on landscape conditions that predated the 2006 Tripod fire. We did not incorporate climate change weather scenarios in the present work; however, subsequent iterations of REBURN can be run in this same landscape to evaluate climate change scenarios using predicted twenty-first-century weather streams.

The Monitoring Trends in Burn Severity (Eidenshink et al. 2007) dataset was used to generate a fire size distribution from fires that intersected the study area between 1984 and 2013. We compared that distribution against the REBURN simulated fire event size distributions over two independent, 3000-year iterations of the model. Next, we used quantitative estimates of early twentieth-century forest structure, composition, size class, and canopy cover conditions from the midscale assessment of the Interior Columbia Basin Management Project study (Hessburg et al. 1999, 2000a, b) to compare against modeled ranges of comparable vegetative conditions across PWGs. The ICBEMP midscale data were derived using standard photogrammetric techniques applied to early twentieth-century subwatersheds. These reconstructed watershed vegetation conditions were extant during the same time as our ignition and weather data and all evidence of early logging was statistically removed via imputation procedures (Hessburg et al. 2007). We selected 16 of these photo-interpreted subwatersheds (mean size = 7685 ha; total sampled area = 122,956 ha) as the sample set for comparison to simulated landscapes. Four subwatersheds were fully within the study area and shared the same biophysical landscape characteristics, and the remainder were in the same biogeoclimatic subregions as our study area (Hessburg et al. 2000b).

Our iterative calibration process involved defining fire event weather parameters, refining the overall structure and parameters of each of the PWG-STMs, and adding these details to the model workflow. For example, defining the fire event duration, and derivative weather-related event stopping rules was a primary influence on generating reasonable fire size distributions. Initial testing showed that an ERC value of 55 generated single-day fire spread to an average of four 90-m pixels, which we then used as the minimum threshold value for a fire growth day. After substantial iterative testing, we established event stopping rules that ended a fire event after two consecutive non-growth days or 14 days. Finally, crown fire spotting probability was set to 0 and the Scott-Reinhardt crown fire model was selected. Combined, these parameters yielded the most reasonable correspondence between FSPro simulated fire size distributions and those from the MTBS dataset.

To develop a final working model, we then iteratively evaluated cases where individual states either burned too severely, routing back to post-fire bare ground, or where old forests (OFMS and OFSS, old forest multi- and single-story states) with frequent low-severity fire accumulated on the landscape in unrealistic proportion (see explanation below). In the context of the published fire severity literature for the Tripod area, we also carefully evaluated all state transitions to fully understand the percentage of pixels within each state that transitioned to another state due to (1) low-, moderate- or high-severity fire, (2) succession in the absence of fire, (3) succession following very low or low-severity fires, or (4) lethal transition to woodland following numerous low-severity fires (Supplementary Table S4). This latter analysis allowed us to locate errors in logic that resulted in unrealistic forest development.

Additional modifications were then implemented in response to the above evaluation to account for special circumstances beyond the scope of the STM transition rules. For example, we assigned an Alt_FBFM within the low-elevation hardwood forest PWG, which generally resided in valley bottoms, and which are often shaded and resistant to burning due to elevated fuel moistures. Through our calibration process, we also determined that a short-term, non-burnable FBFM was needed to account for the post-fire fuel reduction of surface fuels in states that burned at low- to moderate-severity. Finally, some dry pine and dry mixed-conifer states that had low surface fuel conditions with large and old trees acted as unrealistic accumulators of old forest structure because they rarely if ever burned at high severity. Long residence time of these savanna states was unrealistic because the combined influences of historically frequent fires and native forest insects and pathogens acting on old trees in our DMC and MMC PWGs generally allowed trees to survive no more than ~ 14 low severity fires before trees either collapsed or were killed by bark beetles. We derived this number using all existing tree ring datasets within our study area (Everett et al. 2000; Hessl et al. 2004) and the 90th percentile of the full range of fire scar numbers displayed on recorder trees within these studies.

Once these corrections were made to STMs, we conducted a final model evaluation by running two comparative 3300-year simulations (including, a 300-year bare ground spin up period) that evolved through time using random draws from lightning probability and historic weather distributions. These parallel simulations allowed us to detect any important differences in simulated variability of state conditions through time and by replicate. The 3000-year simulations after spin up did not represent a true 3000-year simulation time depth owing to the periods of ignition and weather data. Instead, they represented a time period for all the possible combinations of rare and common wind, weather, terrain, and ignition draws to be represented.

Results

Comparison to reference datasets

Based on a comparison of forest structure class and range of variability conditions for REBURN-simulated and empirical pre-industrial logging period landscape reconstructions, the simulated range of variability (HRV_{sim}) corresponded well with the independently derived empirical ICBEMP HRV_{emp} estimates for the region (Tables 8 and 9). Here, we note that our calibration process did not dictate modeled fire-vegetation dynamics. Rather, model dynamics were allowed to develop independently over time based on interactions between ignition locations, uniform probabilistic draws from historical fire weather, topographic setting, and fuels (Fig. 5).

Some differences were observed in our comparison between simulated (HRV_{sim}) and observed (ICBEMP HRV_{emp} ranges of variability. Specifically, lower elevation DMC forests in HRV_{emp} subwatersheds displayed somewhat more area in stem exclusion open-canopy conditions (SEOC) and less area in old forest single story (OFSS) than shown with HRV_{sim} conditions. Within MMC forests, HRV_{emp} conditions reflected ~ 5% more area in stem exclusion closed-canopy (SECC) and young forest multi-story (YFMS) conditions and somewhat less area in OFSS conditions. HRV_{sim} and HRV_{emp} conditions corresponded well for CDC and CMC forests, with only slightly more YFMS conditions observed within the HRV_{emp} than HRV_{sim}.

Comparison of two 3300-year simulations produced unique combinations of ignition, fire weather, and fuel dynamics over time (Tables 8 and 9); however, the HRV_{sim} of forest structure was remarkably similar

Table 8 Comparison of simulated HRV (HRV_{sim}) with empirical ICBEMP reference conditions (HRV_{emp}) for percentage area by structural class for dry mixed conifer (DMC), moist mixed conifer (MMC), cold moist conifer (CMC) and cold dry conifer (CDC) forests for a *first* 3000-year run of REBURN. Patch structural classes include post-fire bare ground (PFBG), stand initiation (SI), stem exclusion open canopy (SEOC), stem exclusion closed canopy (SECC), understory re-initiation (UR), young forest multi-story (YFMS), old forest multi-story (OFMS), and old forest single story (OFSS)

PWG	Structure	Median	HRV min	HRV10th	HRV 90th	HRV max	ICBEMP % Area	Departure from HRV_{sim}
DMC	PFSI	25.1	12.0	17.7	33.9	46.3	26.3	
DMC	SEOC	20.6	12.4	16.0	25.7	34.0	28.6	+
DMC	SECC	4.6	0.7	2.4	8.5	17.3	2.3	-
DMC	UR	16.8	6.9	11.8	23.7	31.9	16.9	
DMC	YFMS	16.4	9.3	12.1	20.6	27.3	12.8	
DMC	OFMS	5.5	1.0	3.1	9.4	14.7	9.4	
DMC	OFSS	8.9	4.3	6.3	12.1	15.3	3.7	--
MMC	PFSI	19.8	4.7	13.4	28.2	38.8	16.4	
MMC	SEOC	14.9	8.4	12.0	18.8	25.1	11.5	
MMC	SECC	6.3	1.0	3.4	10.7	21.1	11.8	+
MMC	UR	18.9	8.7	13.7	25.6	33.5	23.6	
MMC	YFMS	16.9	9.4	12.7	20.8	26.6	19.6	
MMC	OFMS	8.4	2.2	5.0	12.4	18.9	13.2	+
MMC	OFSS	12.9	8.1	10.4	15.9	21.0	3.8	--
CMC	PFSI	33.6	3.7	14.4	54.8	75.3	32.8	
CMC	SEOC	16.4	8.8	12.3	20.8	28.3	15.0	
CMC	SECC	25.7	1.5	11.7	41.0	60.0	28.3	
CMC	UR	16.9	2.0	7.3	33.2	59.7	16.3	
CMC	YFMS	2.3	0.0	0.9	6.4	31.4	7.0	+
CMC	OFMS	0.4	0.0	0.1	1.9	7.6	0.5	
CMC	OFSS	0.3	0.0	0.1	0.8	2.4	0.2	
CDC	PFSI	38.3	5.0	19.4	56.1	73.5	45.2	
CDC	SEOC	19.4	9.7	14.4	25.2	35.0	17.4	
CDC	SECC	13.5	0.5	5.6	24.5	36.6	13.4	
CDC	UR	22.1	6.2	12.7	35.7	52.9	20.0	
CDC	YFMS	2.5	0.1	0.9	6.0	23.0	2.7	
CDC	OFMS	0.5	0.0	0.1	2.2	4.7	0.1	
CDC	OFSS	0.3	0.0	0.1	0.7	1.1	1.2	++

Table 9 Comparison of simulated HRV (HRV_{sim}) with empirical ICBEMP reference conditions (HRV_{emp}) for percentage area by structural class for dry mixed conifer (DMC), moist mixed conifer (MMC), cold moist conifer (CMC) and cold dry conifer (CDC) forests for a second 3000-year run of REBURN. Patch structural classes include post-fire bare ground (PFBG), stand initiation (SI), stem exclusion open canopy (SEOC), stem exclusion closed canopy (SECC), understory re-initiation (UR), young forest multi-story (YFMS), old forest multi-story (OFMS), and old forest single story (OFSS)

PWG	Structure	Median	HRV min	HRV 10th	HRV 90th	HRV max	ICBEMP % Area	Departure from HRVsim
DMC	PFSI	27.2	9.5	18.6	36.4	48.7	26.3	
DMC	SEOC	20.6	10.7	15.8	26.2	34.8	28.6	+
DMC	SECC	4.6	0.8	2.2	8.7	20.3	2.3	
DMC	UR	16.7	6.8	11.5	23.4	32.9	16.9	
DMC	YFMS	15.6	6.1	11.0	21.5	28.4	12.8	
DMC	OFMS	5.2	1.0	2.5	8.6	14.6	9.4	+
DMC	OFSS	8.1	3.9	5.5	11.9	15.8	3.7	--
MMC	PFSI	21.1	6.0	13.3	29.3	40.0	16.4	
MMC	SEOC	15.3	9.0	11.6	19.1	26.9	11.5	-
MMC	SECC	6.4	0.6	3.1	11.3	21.4	11.8	+
MMC	UR	19.1	8.7	13.8	25.8	35.4	23.6	
MMC	YFMS	16.6	6.3	12.4	20.8	25.6	19.6	
MMC	OFMS	7.4	2.3	4.7	12.4	19.9	13.2	+
MMC	OFSS	12.7	6.2	9.6	15.5	19.5	3.8	--
CMC	PFSI	33.6	2.4	14.0	56.4	74.6	32.8	
CMC	SEOC	16.2	7.8	11.4	21.0	32.1	15.0	
CMC	SECC	25.2	0.8	10.3	44.9	70.0	28.3	
CMC	UR	17.0	2.6	6.2	33.8	58.8	16.3	
CMC	YFMS	2.4	0.1	0.6	6.8	19.9	7.0	+
CMC	OFMS	0.4	0.0	0.1	1.3	5.2	0.5	
CMC	OFSS	0.3	0.0	0.1	0.8	1.4	0.2	
CDC	PFSI	38.3	4.4	18.0	57.2	81.2	45.2	
CDC	SEOC	19.8	9.1	15.0	25.3	46.1	17.4	
CDC	SECC	13.4	0.2	5.1	26.5	48.5	13.4	
CDC	UR	22.0	3.4	12.0	36.1	60.8	20.0	
CDC	YFMS	2.5	0.2	0.7	6.6	17.8	2.7	
CDC	OFMS	0.6	0.0	0.1	1.5	3.5	0.1	
CDC	OFSS	0.3	0.0	0.1	0.6	1.3	1.2	+

between the two, with comparable median, 10th and 90th percentile values, and median 80% ranges of the HRV_{emp} data. Maximum HRV_{sim} values differed from HRV_{emp} values between the two simulation runs, reflecting the unique variety of landscapes that can evolve from unrestricted combinations of fire weather, ignitions, and fuels.

Output maps from REBURN simulations displayed high heterogeneity in vegetation composition and structure over time, and owing to ongoing fire disturbances, no two maps were alike. In Figs. 6 and 7, we present sample output from randomly drawn simulation year 2100 — showing the spatial arrangement of states, their fine to meso-grained patchiness, and associated structural classes, surface fuels, and canopy fuels. Recently burned pixels, represented by post-fire bare ground (PFBG) and stand initiation (newly regenerating forest, SI) conditions, were dominant features of the landscape, particularly in cold, high-elevation forests (Fig. 6). Young forest conditions, represented by stem exclusion open-canopy (SEOC) and understory regeneration (UR) forest, were also common features of this landscape. Patches of multi-story young (YFMS) and old forest (OFMS) were present but were generally fragmented in small to medium-sized patches. Old forest single story

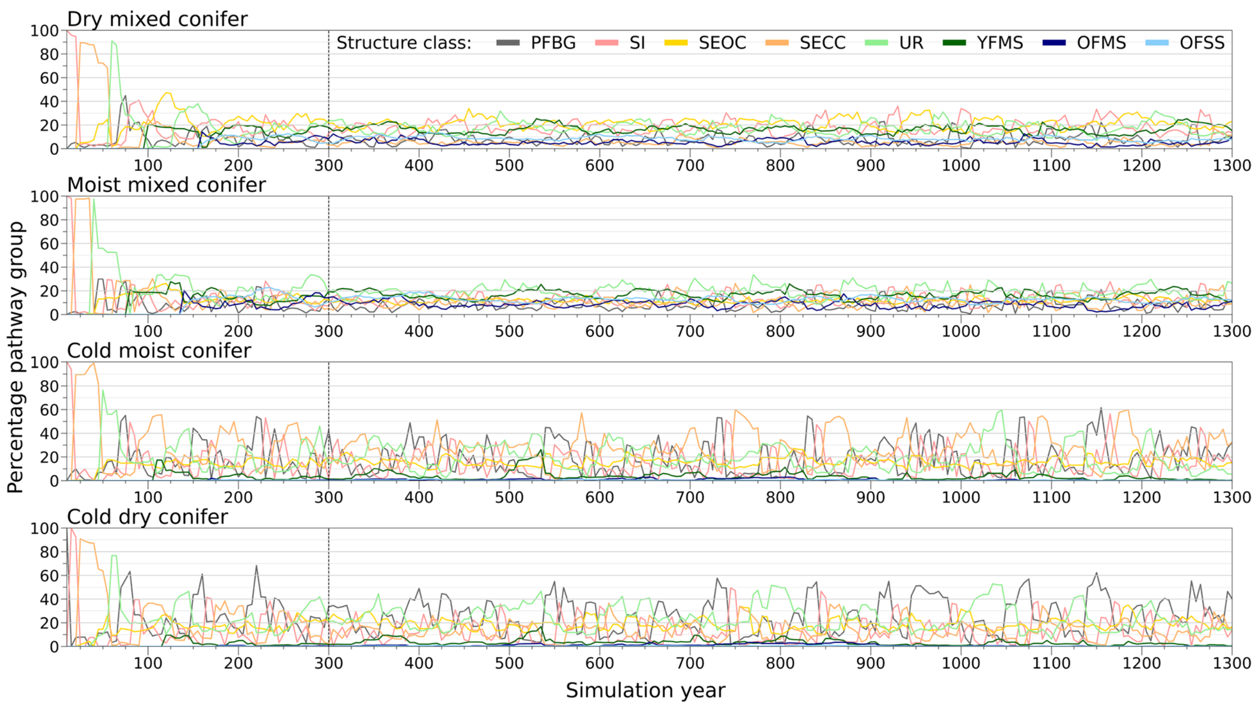

Fig. 5 Traces of REBURN simulated structural class abundance for dry mixed-conifer (DMC), moist mixed-conifer (MMC), cold moist mixed-conifer (CMC), and cold dry mixed-conifer (CDC) pathways showing changes and variation over the centuries. Percent composition by pathway group is displayed over 1300 years for post-fire bare ground (PFBG), stand initiation (SI), stem exclusion open canopy (SEOC), stem exclusion closed canopy (SECC), understory re-initiation (UR), young forest multistory (YFMS), old forest multistory (OFMS), and old forest single story (OFSS) forest structure. The vertical line at year 300 marks the end of the burn-in or spin up period for modeled fire-vegetation dynamics over the first 300 years

(OFSS) was a common structural class within low to mid-elevation dry and moist mixed-conifer forest types and occurred within relatively small patches following fire events.

In Fig. 7, we present two additional views of the simulation year 2100 landscape. Panel A presents the surface FBFM assignments for each output state, with NB9 patches representing surface fuels that were temporary barriers to fire within the most recent fire events. Panel B represents forest canopy cover (%) over the same landscape. Some areas that represent post-fire bare ground have correspondingly low canopy cover, but the majority of burned pixels remained forested with ≥40% canopy cover.

Because REBURN saves state condition outputs on an annual basis, iterative views of landscape patterns and dynamics were possible. For example, in Fig. 8, we present landscape conditions for forest structure of an active Tripod fire regime for simulation years 2125, 2150, 2175, and 2200. Patches of black represent recently burned pixels (FBFM = NB9) after high-severity fire. Light red patches represent regenerating new stand initiation forest, light and dark yellow patches show open (SEOC) and closed (SECC) young forest conditions, while light and dark green patches show UR and YFMS. Light and dark shades of blue represent old OFSS and OFMS forest conditions.

In Fig. 5, post-fire bare ground conditions represented by black traces are especially abundant in high-elevation CDC and CMC cold forests PWGs. Punctuated disturbance events were often precipitated by closed canopy understory re-initiation conditions with high surface and canopy fuel contagion, when fire weather, wind, and slope conditions were suitable for large burns (see Povak et al. 2023 for in-depth analysis). Conversely, in the low to mid-elevation DMC and MMC forest pathway (PWGs), post-fire bare ground area is routinely minimal — owing to frequent fires that remove surface fuels at short intervals, preventing significant dead wood accumulation. Forest development in Fig. 6 occurs in the D and F pathways of the DMC and MMC forest types — revealing that these PWGs are primarily influenced by multiple reburns.

Because each state within REBURN STMs was assigned an FCCS fuelbed, calculations of total aboveground biomass and carbon by state were possible (Table 10). MMC forests in the fire exclusion pathway hold the greatest total aboveground carbon, followed by CMC forests. Total aboveground carbon stores are around 25–50% lower within moderate-severity pathways (B–F).

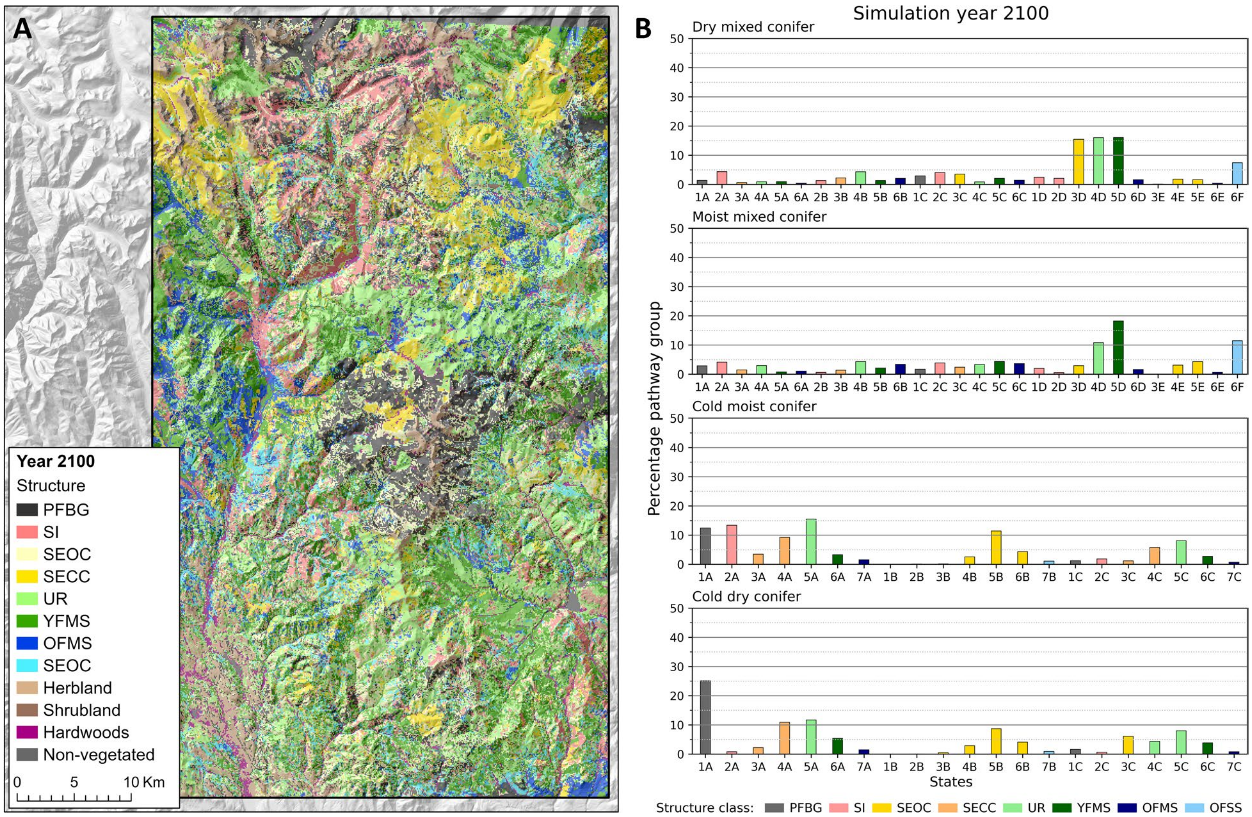

Fig. 6 **A** Map of structural classes for simulation year (2100) of one of two 3300 years REBURN simulations, including post-fire bare ground (PFBG), stand initiation (SI), stem exclusion open canopy (SEOC), stem exclusion closed canopy (SECC), understory re-initiation (UR), young forest multistory (YFMS), old forest multistory (OFMS) and old forest single story (OFSS) forest structural conditions, and herbland, shrubland, hardwoods, and non-vegetated areas. **B** Corresponding bar chart showing the percentage composition off each state in the modeled landscape. States are those shown in STM Figs. 3 and 4 and described in the Discussion section—State-transition models

Discussion

Model calibration

We developed the REBURN modeling framework to evaluate the impacts of twentieth-century fire exclusion on forest conditions and their wildfire vulnerability, and to explore the attributes of an active fire regime on the Tripod forest landscape. REBURN's design also enabled us to compare the dynamics of forest reburning, fire event sizes, and fire severity patch size distributions with and without an active fire regime, and to observe forest development tipping points and the conditions that precipitated them.

To explore patterns of forest vegetation and fuels across recurrently reburned landscapes, we created an iterative and recursive GIS and fire growth modeling workflow that used annual historical ignition and weather data to evaluate likely burn mosaics resulting from combined ignitions, surface and canopy fuel patterns, and actual fire weather and topography. Model outputs enabled us to visualize representative effects of fires on subsequent ignitions, fire spread, and fire constraint by means of fire-fire interactions over space and time (see Povak et al. 2023). Simulations revealed how lagged effects of spatial time-since-fire patterns and fire weather conditions influenced the ability of fire-fire interactions to constrain (fences) or enable (corridors) fire growth and fire severity patterns over time. Lagged reburn memories provided a potent influence on future fire event sizes and their severity patch sizes.

REBURN was developed to assess local- and regional-scale dynamics over long time frames. However, model functionality is not limited to these analyses. REBURN can also be used to compare current and future wildfire management and mitigation strategies and their efficacy in constraining fire growth and severity patterns, which is the focus of forthcoming modeling efforts and manuscripts. In addition, REBURN can be used to evaluate the effects of climatic warming on active fire regime characteristics, forest and nonforest abundance, alternative ignition scenarios (e.g., incorporating Indigenous cultural burning or contemporary human ignitions), and the frequency and severity of forest

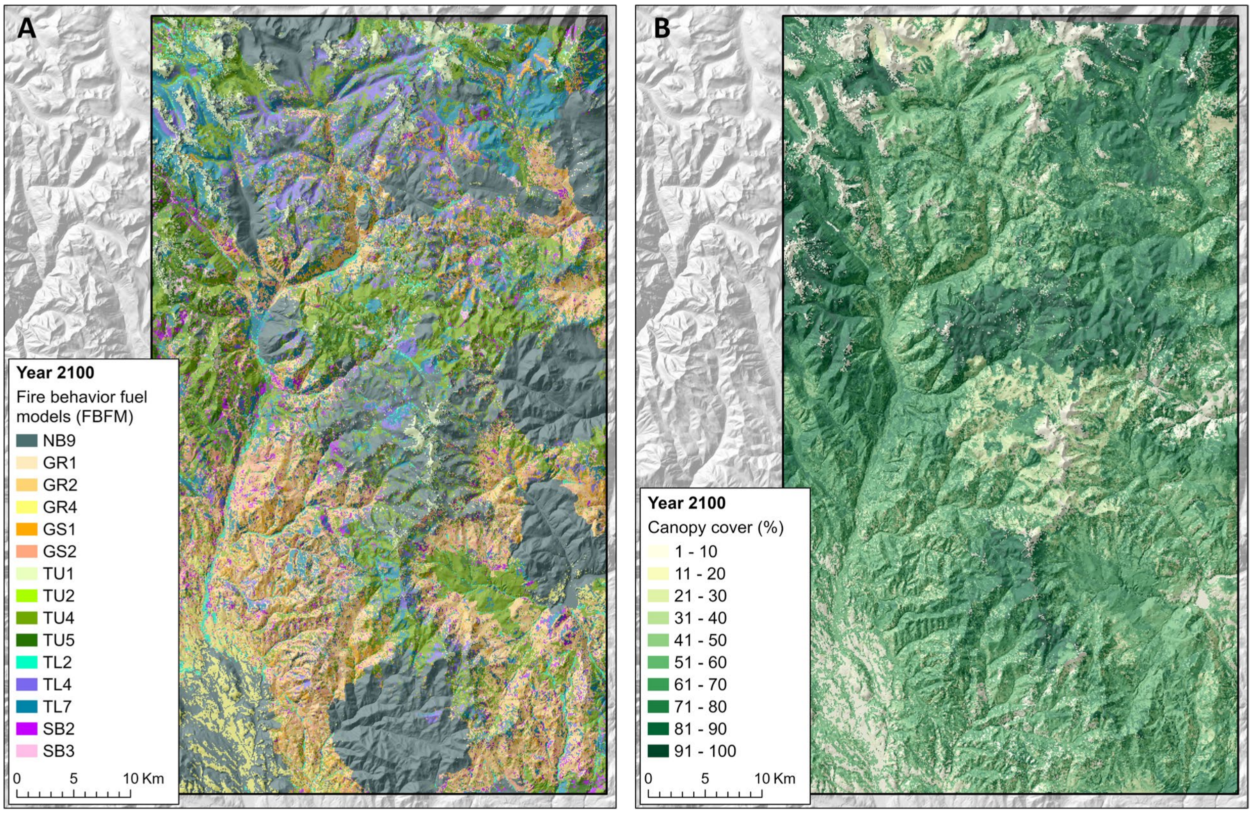

Fig. 7 Sample output maps for year 2100 of a REBURN simulation showing spatial patchiness of **A**) surface fire behavior fuel models and **B**) canopy cover

reburning. The results from initial REBURN modeling provide a unique perspective on the long-term consequences of twentieth- and early twenty-first-century wildfire management decisions — in particular, the influence of long-term fire suppression decisions on future wildfire event sizes and their severity patterns.

Patterns of vegetation structure and composition across the landscape simulations offer important perspectives regarding the characteristics of active fire regimes and on restoring their role within our study area landscapes. Across the two 3300-year simulations, fire-vegetation interactions maintained a range of forest and nonforest ages and structural conditions (Fig. 5). At any one time, nonforest conditions (primarily on sites with high potential to produce forested land cover), including post-fire bare ground and stand initiation structure after high severity fire, ranged from 35 to 50% of the total landscape area (see Povak et al. 2023), an estimated range that matches well with nonforest reconstructions recently published for this province in Hessburg et al. (2019: Table 1, Northern Glaciated Mountains province, 43.5%).

Following an initial 300-year burn-in period, fire-vegetation dynamics markedly differed between lower elevation mixed-conifer and upper-elevation cold forests. Specifically, cold forests experienced longer periods of forest accretion and biomass accumulation followed by spikes in post-fire bare ground deriving from synchronous medium to large-sized fires and patches of high-severity fire. Such fires generally burned large portions of the study area over fairly short intervals, e.g., every 50–100 years. In contrast, lower-elevation forests exhibited much finer spatial and temporal variability in structural class composition, suggesting that stand replacement events were smaller and less common. Within these DMC and MMC forests, a broad range of forest structure conditions and patch sizes were supported by frequent fires of varying but mostly low and moderate severity.

Simulated ranges of variability (HRV_{sim}) by PWG (Tables 8 and 9) reveal that although a wide range of forest structures was supported by active fire regimes, old and mature forests were common but not dominant features within the landscape. For example, multistoried old forests (OFMS) comprised less than 15% of DMC and MMC forests in both the ICBEMP dataset and REBURN simulations. Based on median HRV_{sim} values, OFSS forests comprised between 9 and 13% of

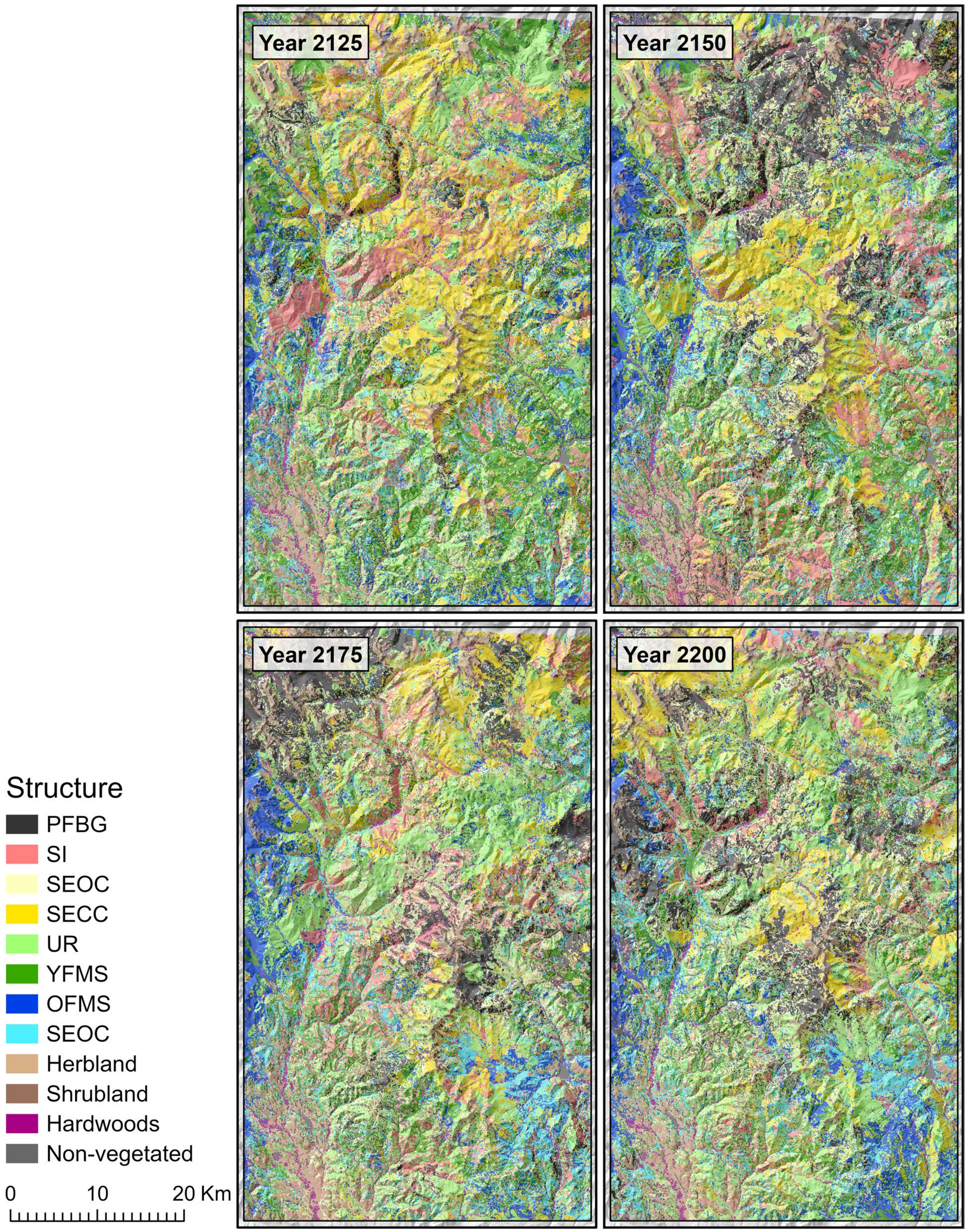

Fig. 8 Example of forest structural dynamics over time from simulation year 2125 to 2200. Structural classes include post-fire bare ground (PFBG), stand initiation (SI), stem exclusion open canopy (SEOC), stem exclusion closed canopy (SECC), understory re-initiation (UR), young forest multistory (YFMS), old forest multistory (OFMS) and old forest single story (OFSS), and herbland, shrubland, hardwoods, and non-vegetated conditions

Table 10 Estimated total aboveground carbon (mg/ha) by each state within the dry mixed conifer, moist mixed conifer, cold moist conifer, and cold dry conifer state and transition model pathways based on output from the Fuel Characteristics Classification System

State	1	2	3	4	5	6	7
Dry mixed conifer							
A	19.9	22.3	63.0	76.5	95.5	117.5	
B		13.0	53.3	62.0	63.0	72.5	
C	0.1	0.9	29.9	52.3	89.4	97.9	
D	0.1	1.0	21.6	31.2	48.7	54.3	
E			26.7	34.6	46.1	44.3	
F						27.7	
Moist mixed conifer							
A	28.0	25.0	79.7	100.9	135.7	175.4	
B		18.2	65.0	73.9	74.3	88.0	
C	0.1	0.9	37.1	63.0	125.5	133.0	
D	0.2	1.0	26.6	38.4	67.6	72.8	
E			32.8	42.1	63.6	60.9	
F						34.3	
Cold moist conifer							
A	13.0	27.6	54.8	62.3	90.7	116.1	139.5
B	1.7	56.5	42.5	39.4	57.6	75.3	99.4
C	0.0	0.2	37.4	52.8	84.2	102.2	117.0
Cold dry conifer							
A	11.7	8.6	46.7	52.3	74.6	96.3	114.1
B	3.3	37.5	33.3	35.0	46.9	61.0	81.3
C	0.0	0.2	30.5	43.6	65.6	79.3	89.4

low-elevation DMC and MMC forests, which is a somewhat higher estimate than provided by the ICBEMP reference dataset.

With longer fire return intervals, late-successional and old forests were even less abundant in cold forests, with < 2% of CDC and CMC forests in old forest structures. Owing to relatively active fire regimes with much moderate and high-severity fire, it was uncommon for patches of forest to get old (see the detailed analysis in Povak et al. 2023). This is a key finding that was also reflected in reconstructed patterns of historical cold forest structure in our study area (Hessburg et al. 1999). Old forests did not dominate in Tripod area cold forests. Much of our current knowledge of cold forest successional conditions and their wildfire dynamics derives from fire-excluded forests and their associated habitat conditions. The HRV_{emp} dataset showed a somewhat higher composition of old forests in CMC types, but estimates were within 10–20% of historical reference estimates.

State-transition models

The calibrated STMs developed in this study are foundational to the REBURN modeling framework. Each state is populated with canopy and surface fuel inputs that can be used in operational fire behavior models including FlamMap, FARSITE, FSPro, and FSim, which are used and supported by wildland fire managers within the Wildland Fire Decision Support System-WFDSS (NWCG). Although the pathways are multifaceted, particularly within the DMC and MMC models, these STMs are representative of the multiple states that are supported by reburning in these forest types (Hessburg et al. 2007, 2016; Perry et al. 2011). To date, the STMs include DMC, MMC, CMC, and CDC forests. To expand the utility of these STMs, we are now working with this base model to build revised STMs that adequately represent mixed assemblages of aspen within MMC and CMC conifer forests as well as management pathways that include forest thinning, regeneration harvests, and prescribed burning.

Forest insects and diseases are common disturbance agents in these forest types as well, especially in the absence of fires, and they contribute to changing forest structural conditions and their surface and canopy fuel successional dynamics. Future work on STM modeling could include bark beetle outbreaks by relevant host-specialized species in each PWG using empirically supported frequencies and event sizes. It is likely that these modifications will double or triple the complexity of the STMs, and they were well beyond the scope of this study.

One of the novel aspects of this study is that the spatial STMs in REBURN were not designed with probabilistic transitions and did not resolve to a calibrated end point (Blankenship et al. 2021). This is a shortcoming of some existing STM models because there is limited opportunity for surprises, for example, like discovering landscape tipping points, or the significant emergence of nonforest conditions in sometimes shifting forest-capable settings and their outsized role in maintaining landscape resilience. With REBURN, unique combinations of ignitions, fire weather, topography, and fuel conditions allowed the model to have run-wild properties that create fire-vegetation feedbacks without upfront specification of fire size distributions or vegetation feedbacks to fire. Instead, fire event size distributions and fire severity patch size distributions emerge from long-term simulations involving fire-fire and fire-vegetation interactions. This is a highly significant difference with other STM-based models. Starting with a barren landscape, REBURN grows vegetation according to STM time steps and then dynamically models fire-vegetation interactions over time from lightning probability and historical weather data. Following, we detail the final, calibrated STM pathways in PWGs.

Low-elevation forests

The calibrated DMC and MMC models presented here represent highly heterogeneous and dynamic (i.e., continuously shifting) forest successional development over space and time, associated with a spatially and temporally variable severity fire (Figs. 3 and 4). By supporting an intentionally limited number of states, aligning time steps across successional stages, and ramping transitions annually between states, the STMs offer a simplified, representative, and sufficiently nuanced depiction of fire and vegetation dynamics over a broad range of burn severities. Combinations of varied fire severity created a continuum of states, reflecting myriad fire effects and emergent forest and fuelbed structures, conditions that must be simplified to make modeling manageable.

The DMC model depicts fire-vegetation dynamics in low-elevation and dry-aspect forests (Table 3). The MMC model shares the same pathways and states as the DMC but with shorter times between states and differing canopy fuel assignments, representing greater productivity and more rapid development of stand structure over time (Table 4). The following discussion characterizes DMC pathways and their associated time steps in the STM. Even though forest productivity is represented as greater in the MMC pathway, we assumed fires were the primary driver of surface fuel accumulations and replicated surface fuel assignments used in the DMC pathway but varied the succession time steps and the associated ramp functions associated with surface and canopy fuel bed transitions.

The "*fire exclusion*" pathway, A, depicted forest development after a stand-replacing fire event from post-fire bare ground (1A) to > 160-year-old multistoried DMC forests (6A) in the absence of any subsequent fire. State 1A (0–9 years) represents post-fire bare ground with mostly exposed soil and burned grasses and herbs, standing dead trees (snags), and coarse wood remaining from the antecedent forest. Surface fuels are discontinuous, posing a barrier to fire spread, which is well supported by recent studies in our study area (Prichard and Kennedy 2014; Stevens-Rumann et al. 2016). However, during the period of State 2A (10–24 years), a reburn is possible in surface fuels dominated by regrown grass and litter with scattered medium and large-sized logs. By 3A (25–59 years), heavy accumulations of dead wood from the antecedent stand are present (see Peterson et al. 2015), and by State 4A (60–99 years) understory trees and accumulations of litter and fine wood have accumulated in maturing forests due to stand dynamics processes. In the continued absence of moderate- or high-severity fire, State 5A (100–159 years) forests have developed multiple canopy layers of shade-tolerant trees and high surface fuel loads. State 6A (≥ 160 years) represents maturation to a beginning old forest state, with multilayered canopies and heavy surface fuels, snags, and down logs that have developed in the prolonged absence of fire. In states 3A to 6A, a high-severity fire returns DMC sites to State 1A.

The "*low-severity*" DMC reburn pathway B represents reburn scenarios in which subsequent reburns support modest reductions in canopy fuels and in most B pathway states, a reduction in surface fuels. State 2B (10–24 years) represents a low- or moderate-severity reburn of 2A with reductions in regenerating trees and surface fuels and an open canopy condition. States 3B (25–59 years) and 4B (60–99 years) represent increasingly open forests created from low-severity burns in 3A and 4A, respectively, with a modest reduction in surface fuels in 3B, and no significant change in 4B. In many cases, individual low-severity fire events initially reduce surface fuels but also recruit new fuels through crown scorch and pockets of tree mortality (Agee 1996, Agee and Lolley 2006). In 5B (80–159 years), reduced canopy cover is created from low-severity fires in 5C, with no net change in surface fuels. State 6B (160–200 years) represents an open-canopy, single-story old forest that has developed after low-severity fire in 6C and 6E.

The "*high-severity reburn*" pathway C reflects forest and fuel succession after a high-severity fire in regenerating forests, and in later stages (5C and 6C), old forest development under more open canopy conditions than were present in pathway A. High-severity reburns consumed antecedent snags and logs, leading to delayed surface and canopy fuel succession due to reduced seed source and/or competition with established grasses (Stevens-Rumann et al. 2016; Stevens-Rumann and Morgan 2019). State 1C (0–9 years) represents post-fire bare ground after stand-replacing fires in 2A, 2B, and 1D. Antecedent snags and logs are absent and stand initiation is sparse due to lack of seed source. Subsequent fires are not possible at this state. After 9 years, stands without additional fire transition to State 2C (10–24 years), representing an open-grown regenerating forest with sparse surface fuels following succession from 2A, or a low-severity reburn of 2B. By State 3C (25–59 years), an open-grown young forest has either developed from State 2C or 2D, or via a low-severity reburn in 3B. State 4C (60–99 years) is an open canopy forest with some understory tree recruitment in the absence of fire in 3C, 3D, and 3E. State 5C (100–159 years) represents a maturing forest with multiple canopy layers that have reduced surface fuels due to low-severity fire in 5A, or forest and fuel succession following no fire in States 4B, 4D and 4E. State 6C (≥ 160 years) represents an old forest with understory tree recruitment and reduced surface fuels, resulting from a low-severity fire in 6A, or forest succession in the absence of fire in states 5D and 5E.

The "*frequent fire*" pathway D tracks multi-aged forests that developed within repeated low- and/or moderate-severity fires. Because this pathway represents frequent fires and light understory fuels, we show that states advance through successional time after a low-severity fire event, as represented by dashed arrows in the STM diagram (Fig. 2). State 1D (0–9 years) represents a sparse dry mixed-conifer woodland with scant surface fuels after multiple moderate-severity burns across a range of states in the B, C, D and E pathways. Old forests with over 14 low-severity fires are returned to State 1D due to the gradual collapse of overstory trees by reburning old fire scars or by second-order fire effects and bark beetle mass attack. State 2D (10–24 years) represents a woodland or savanna form of stand initiation with very sparse seedling and sapling tree cover, and light, grass-dominated understory fuels. Following multiple low- and/or moderate-severity fires, State 3D (25–59 years) is a young open grown forest or woodland. States 4D (60–99 years) and 5D (100–159 years) are maturing open-grown forests that develop through multiple low to moderate-severity fires. State 6D (160–199 years) represents an open-grown old forest with some canopy layering due to episodic recruitment of younger trees and the patchy nature of low- and moderate-severity fires. In the absence of fire within each state, forests transition to Pathway C, representing somewhat denser forests and greater surface fuel accumulations.

The "*moderate-severity*" pathway E follows moderate-severity wildfires that create somewhat larger forest openings than low-severity fires and elevated surface fuels resulting from patchy post-fire tree mortality. State 3E (25–59 years) represents an open, young forest that had a moderate-severity fire in either state 3A or 3B that resulted in 20–70% mortality of trees, and recruitment of significant surface fuels. Similarly, states 4E and 5E follow maturing forests with reduced canopy cover and comparable or elevated surface fuels from moderate-severity fires in 4A or 4B, or 5A and 5B, respectively. State 6E (160–199 years) represents patchy, old forests with high accumulations of downed and dead wood after a moderate-severity fire in 6A. Absent fire, all E pathway states transition to the C pathway, representing forests with lower canopy cover than displayed in pathway A, but accumulated surface fuels from prolonged fire exclusion.

The "*savanna*" pathway F contains a single state representing a ponderosa pine-dominated savanna with few scattered Douglas-fir composed of old, open-grown trees with grass-dominated surface fuels. Low-severity fires maintain this state, while in the absence of fire, the state transitions to 6C. Over time, a moderate-severity fire or repeat low-severity fires ($n > 14$) create a very sparsely treed woodland or primarily grassland state, represented by State 1D.

Cold forests

The CDC and CMC STMs follow fire and fuel dynamics of high-elevation, cold mixed-conifer forests. Dry-site CDC forests are located below exposed ridges, with often shallow, well-drained, and coarse-grained soils, on slopes with southern or western exposures, and in flat high elevation, high insolation aspects. Early successional CDC forests are dominated by lodgepole pine with gradual recruitment of shade-tolerant Engelmann spruce and subalpine fir in the absence of fire. In many pre-colonial CDC forests, tree cover likely occurred in dispersed patches or copses with favorable moisture or microsite conditions (Hessburg et al. 2000a, 2019). CMC forests exist on moister, productive sites including valley bottoms, moist benches, and north and east-facing slopes, where water and snowpack to support growth are generally not limiting. Depending on disturbance history, early successional CMC forests are pure or mixed assemblages of Engelmann spruce-subalpine fir-lodgepole pine with more canopy layering and correspondingly lower canopy base heights. Although surface fuel succession and fire-vegetation dynamics likely differed somewhat between CDC and more productive CMC forests, owing to fire exclusion, we lacked sufficient reburn field data to distinguish notable differences and hence, modeled surface fuel dynamics as approximately the same with differing surface and canopy fuel succession rates (Table 4). The following description follows CDC fire and vegetation dynamics across three main pathways. Since CMC are generally more productive, the timing of state transitions reflects more rapid forest structural development.

The CDC "*fire exclusion*" pathway A follows vegetation recovery and succession after a stand replacement fire (Fig. 4). In States 1A through 7A, a cold CDC forest develops over >180 years in the absence of any subsequent fire. State 1A (0–14 years) represents stand initiation (SI) of mostly lodgepole pine after high-severity fire, where bare ground dominates, and snags and coarse wood remain from the antecedent stand. Surface fuels are discontinuous and limit fire spread for a time. After 14 years without fire, 1A succeeds to 2A. In 2A (15–24 years) subsequent fires are possible in light surface fuels dominated by compact timber litter, herbaceous fuels, and low shrubs (Stevens-Rumann et al. 2016).

In the continued absence of fire (State 3A, 25–39 years), a regenerating forest dominated by small-diameter lodgepole pine has a closed canopy and a light grass-shrub understory. State 4A (40–59 years) represents a continuation of this stem exclusion-closed canopy condition (SECC), but with larger dense trees and sparse understory vegetation. By State 5A (60–119 years), absent fire, Engelmann spruce, and subalpine fir have recruited in the understory, creating multiple canopy layers and elevated surface fuels. State 6A (120–179 years) represents forest patches with multiple canopy layers and heavy accumulations of live and dead surface fuels via stand dynamics and crown abrasion processes. In the continued absence of fire, old forests with multiple canopy layers have developed by State 7A (≥180 years) with heavy surface fuel accumulations from individual or group tree mortality from natural thinning, bark beetles, and root diseases in spruce and subalpine fir.

The "*moderate-severity*" pathway B follows CDC and CMC forest development following low- to moderate-severity reburns in pathways A and C as well as forest succession along pathway B. As indicated by a lack of arrows to this state in the pathway diagram, State 1B (0–14 years) is unique within the STMs. Old forests eventually succumb to old age, via insect and pathogen attacks over time. In, the rare event that old forests in 7A, 7B, or 7C live over 100 years past the maximum time in state (219 years) or have over 14 low-severity fire events, they return to an open canopy woodland, represented by State 1B. These conditions very rarely occurred in model simulations. State 2B follows low-severity fires in either State 1B or 2A that reduced surface fuels and created patchy mortality within regenerating forests. States 3B through 7B represent open, patchy forests following moderate-severity burns that generally maintained or amplified surface fuels associated with extensive post-fire tree mortality among thin-barked trees. Dotted arrows in the pathway diagram indicate that forests along the B pathway succeed to the next state if they experienced low-severity fire(s) sometime during that state. Absent fire, states 1B-7B transition to the fire exclusion pathway A. For example, if no fire occurred between 15 and 24 years in State 2B, it advances to State 3A (25–39 years). High-severity fires of States 3B through 7B return conditions to State 1A. Moderate-severity fires in the B pathway represent a second moderate-severity fire in States 4B and 7B, and the STM projects that after the second moderate-severity fire, few mature trees remain alive, and sites were best represented by State 1A.

The "*high-severity reburn*" pathway C represents the trajectory of sites that were burned by a subsequent high-severity fire in early stages of forest regeneration (States 1B, 2A, 2B, and 2C). Rates of tree recruitment and fuel accumulation are relatively slow in State 1C, reflecting a lack of seed source and that snags from the antecedent stand were consumed in the second fire event. Because regenerating Engelmann spruce-subalpine fir-lodgepole pine forests grow slowly and have thin bark and low crown base heights, a moderate-severity fire in 3B also transitions conditions to State 1C. In the absence of a subsequent fire, the state succeeds to 2C, which represents discontinuous, sparse surface fuels and a prolonged stand initiation phase associated with slow rates of tree regeneration. In the continued absence of fire, forests develop along States 3C and 7C with slow rates of surface fuel accumulation due to the combined effects of the original high-severity reburn that consumed downed wood associated with the antecedent fire and low site productivity. As indicated by the dotted arrows on the C pathway, we model low-severity fires as having little influence on states; affected pixels transitioned to the next state. Low-severity fires in high-elevation cold forest are often ground fires in wet or dry meadows with low or patchy tree mortality. However, after repeated low-severity fires, sites transition to State 1B, representing open subalpine parks or woodlands with well-dispersed meadows.

Conclusions

Prior to the 2006 Tripod Complex fire, the study area was dominated by mature forests following a long absence of fire. Since 1945, over 300 fire starts were suppressed within the Tripod perimeter alone. Once extensive subalpine wet and dry meadows had been colonized by trees and broad differences in successional conditions had blended into apparently homogeneous conditions. A long period of fire exclusion was unprecedented for this relatively frequent fire landscape, leaving large amounts of mature forests, particularly at higher elevations. The lack of ecological memory (sensu Peterson 2002) normally associated with past fires strongly influenced subsequent fire behavior and effects. In the case of the Tripod 2006 burned landscape, much of the area burned within patches of stand replacement (Prichard and Kennedy 2014), followed by generally abundant post-fire regeneration of serotinous lodgepole pine or western larch (Littlefield 2019). Unless active fire management is applied to break up forest continuity (Lyons et al. 2023), future drying trends in the region and the potential for increased lightning activity suggest that fire will play an increasingly important role in this synchronized and compositionally simplified landscape as it recovers (Li et al. 2020; Abatzoglou et al. 2021; Harvey et al. 2023).

REBURN modeling of frequent (1 to 15 years), moderately frequent, (15 to 30 years), and moderately infrequent (30 to 50 years) fire within the Tripod landscape offers insight for how fire-vegetation interactions may have shaped this landscape had fire not been excluded. Wildland fire management decisions that allow unplanned ignitions to burn or be fully suppressed within this area have significant legacy implications for future patterns of vegetation and wildfires (Parks et al. 2012, 2015). For 15 years, the 2006 Tripod Complex Fire was a barrier to fire spread in subsequent large wildfire events, including the 2014 Carlton Complex and 2015 Okanogan Complex fires. However, by 2021, (15 years hence), lower elevations within the Tripod burn scar were available to reburn as was observed in the Cub Creek II Fire (Washington Department of Natural Resources, Forest Resilience Science Team 2021). A return of prescribed fire or managed wildfire to the Tripod landscape today will set 2006 burned areas on trajectories of temporally varied fire severity, whereas complete suppression will predispose the landscape to future large and severe wildfires (Stevens-Rumann et al. 2016; Prichard et al. 2017; Lyons et al. 2023), which will have significant consequences for native Canada lynx populations.

As the incidence and area burned by wildfires is increasing in wNA, carbon fluxes, and smoke emissions from recent wildfires are of increasing concern (Liu et al. 2017; Li et al. 2020; Burke et al. 2021). Because each state within the STMs is accompanied by an FCCS fuelbed, we can estimate total aboveground biomass and carbon, which can be used to evaluate potential wildland fire emissions and the sustainability of carbon sinks and stocks under different wildfire management scenarios (Table 10, Additional File S3). These reported estimates are within a reasonable range based on comparisons with Gholz (1982), who estimated total aboveground biomass across major vegetation zones of Oregon, including drier, east Cascades forest types. Within our PWG STMs, estimates of total aboveground carbon are 25–50% higher in older, fire-excluded states than in those with active fire regimes. For example, old moist mixed-conifer forests, as represented by state MMC 6A, are estimated to have 175.4 Mg/ha of total aboveground carbon compared to a range of 34.3 to 133 Mg/ha in old forests in B to F pathways. Since active fire regimes are returning to interior forest landscapes, future analyses of carbon dynamics within REBURN are planned to evaluate realistic ranges of total aboveground carbon under restored fire regimes.

By constructing and associating FCCS fuelbeds to represent each state within the pathways, REBURN also offers a crosswalk between the states and early to late-successional forest structure and wildlife habitat conditions, as well as to aboveground biomass estimates that can be used for evaluating carbon dynamics and potential wildfire smoke and emissions scenarios (Hurteau and Brooks 2011; Loehman et al. 2014).

In another application of REBURN in the Tripod landscape, we are evaluating variation in early, mid-, and late-successional forest habitat. Large high-severity wildfires, such as the 2006 Tripod Complex fires have had significant impacts on Canada lynx (*Lynx canadensis*) habitat use and availability (Vanbianchi et al. 2017a, b). The CDC and CMC pathways were designed with surface and canopy fuel states that are highly relevant to lynx, including young, dense CMC forests that retain some understory vegetation and cover (States 3A, 3B, and 2C, lynx foraging habitats for snowshoe hare), and somewhat older, multi-storied forests with large amounts of coarse down wood and optimal lynx denning habitat (States 7A, 6C). This crosswalk between the STMs, a ranking of suitable lynx denning and foraging habitat conditions, and their spatial distributions makes this model useful for examining management scenarios that can create forest landscape conditions that are less vulnerable to wildfires, while accounting for associated effects on key lynx habitats and their proximities.

Forest ecosystems that were historically influenced by spatially and temporally mixed-severity fire regimes are at a critical crossroads. Due to a notable lack of reference sites for establishing variability in forest successional conditions, simulation modeling is one of the best options for evaluating the consequences of

EuroAmerican colonization, past and present fire management, and future adaptation strategies. In addition, reference sites will be unavailable for projecting likely successional conditions under rapid climate change, and simulation modeling, such as we have presented, will be required. By dynamically simulating the variability of wildfire events within and across wildfire seasons and forest and fuel succession over that same timeframe, the REBURN model allows for incorporating the role of extreme weather and wildfire events *and* evaluation of the role of variably sized fire events in providing negative feedbacks to the flow of large and severe fires across the landscape. We explore this further within our companion paper (Povak et al. 2023).

In this paper, we introduced and fully described the calibrated REBURN model and presented spatially and temporally mixed-severity STMs that represent common forest types within wNA. Although the STMs were originally created within a simulation tool, they also contain forest structural and biomass datasets that are relevant to wildlife habitat suitability, carbon accounting, and wildland fire emissions inventories under various management regimes. In future articles, we will present the results of REBURN modeling in the Tripod landscape under the influence of the twentieth-century climate (Povak et al. 2023), under twenty-first-century climate change, and when implementing various fire management scenarios as alternatives to full fire suppression.

Abbreviations

Alt_FBFM	Alternative fire behavior fuel model
CDC	Cold dry conifer
CMC	Cold moist-conifer
DMC	Dry mixed-conifer
ERC	Energy Release Component
FBFM	Fire behavior fuel model
FCCS	Fuel Characteristics Classification System
FFE	Fire and fuel extension of FVS
FOFEM	First Order Fire Effects Model
FVS	Forest Vegetation Simulator Fire and Fuels Extension
FW13	Common weather observation data transfer format
GIS	Geographic Information System
HRV_{emp}	Empirical historical range of variability (from the ICBMP)
HRV_{sim}	Simulated historical range of variability (from REBURN)
ICBEMP	Interior Columbia Basin Management Project
LCP	Landscape file for fire growth modeling
MMC	Moist mixed-conifer
OFMS	Old forest multistory
OFSS	Old forest single story
PFBG	Post-fire bare ground
PWG	Pathway group
RAWS	Remote Automated Weather Station
SECC	Stem exclusion closed canopy
SEOC	Stem exclusion open canopy
SI	Stand initiation
STM	State transition model
VIC	Variable Infiltration Capacity
wNA	Western North America
YFMS	Young forest multistory

Supplementary Information

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Additional file 1: Table S1. State burn severity and successional transitions for states in the dry mixed conifer (DMC), moist mixed conifer (MMC) pathway groups (PWGs). **Table S2.** State burn severity and successional transitions for states in the cold dry conifer (CDC) and cold moist mixed-conifer (CMC) pathway groups (PWGs). **Table S3.** FCCS inputs and outputs. **Table S4.** Percentage of pixels transitioning from each state within the DMC, MMC, CDC, and CMC STM pathway groups via low, moderate, and high severity fire, succession in the absence of fire (NoBurnT), succession after very low or low severity fires within that state (BurnedT), or a lethal transition to woodland following repeated low severity fires (Lethal). Burn severity classes at the right of the table report the percentage of pixels burned at very low, low, moderate and high severity classes by state ID.

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Authors' contributions
SJP, RBS, PFH, and NAP all contributed to the manuscript writing. SJP: funding, conceptualization, data preparation, writing—original draft preparation, and writing—review and editing; RBS: conceptualization, data preparation, and writing—review and editing; PFH: funding, conceptualization, data preparation and analysis, writing—original draft preparation, and writing—review and editing; NAP: writing—review and editing. RWG: conceptualization, data preparation, and writing—review and editing. The author(s) read and approved the final manuscript.

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Availability of data and materials
Datasets generated and analysis during the current study area available at for reviewing at: https://osf.io/6kczh/?view_only=623dbe9bf6d94c7880627b4f41f5ad83. Note: this will be replaced with a public doi upon publication.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

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

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