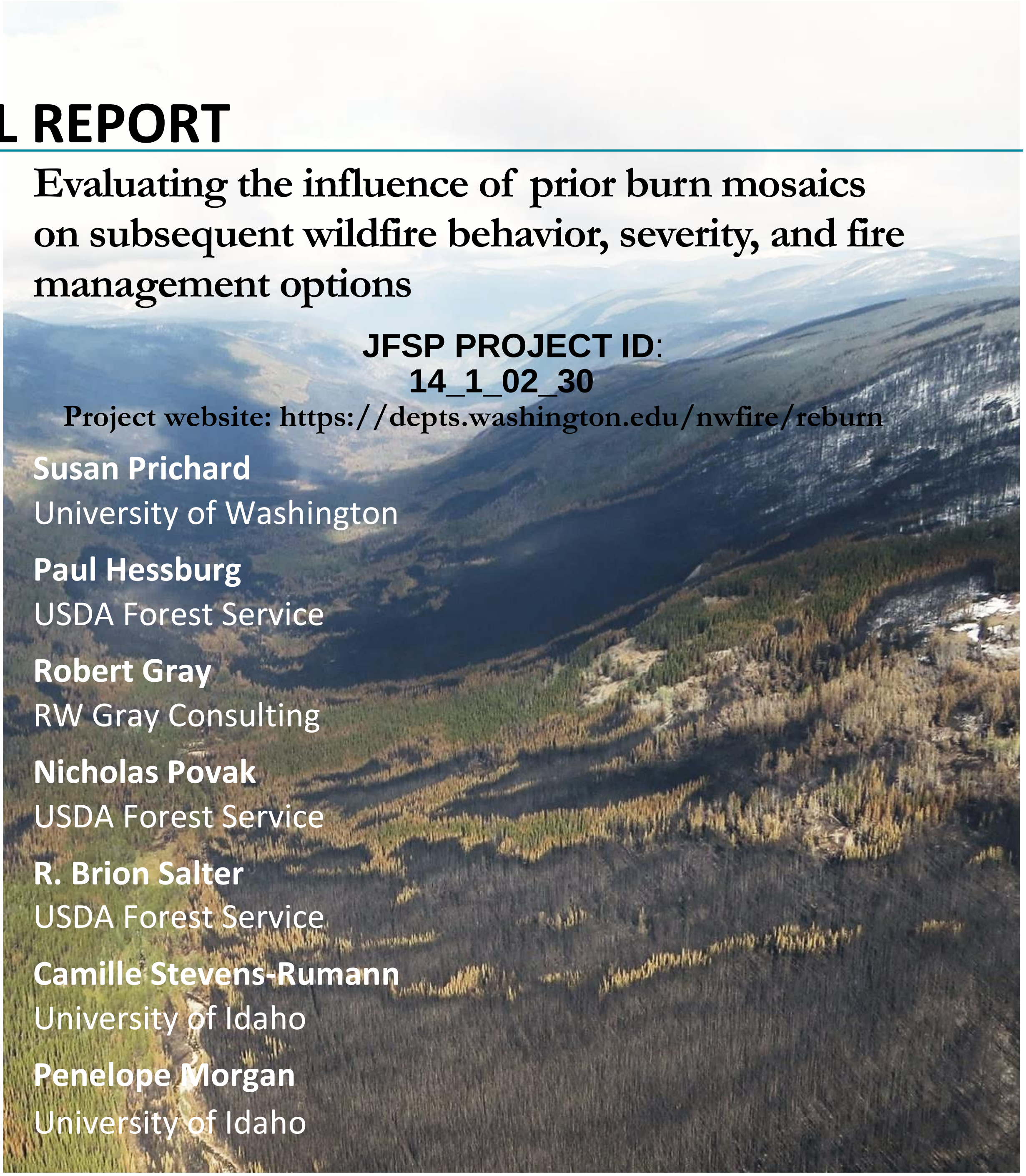
FINAL REPORT



Evaluating the influence of prior burn mosaics on subsequent wildfire behavior, severity, and fire management options

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Abstract

The Reburn Project was motivated by a need to better understand wildfires as fuel reduction treatments and to assess the impacts of decades of wildland fire suppression activities on forested landscapes. Our study examined three areas, located in the inland Pacific Northwest, central Idaho and interior British Columbia. Each area had experienced a recent large wildfire event in montane forests.

Our first objective was to evaluate what is known about fire-fire interactions and their influence on subsequent large fire events. A second objective was to evaluate how past wildfires might function as transient barriers to subsequent wildfire spread and the effect that landscape position, fire weather, and fireline position (heading or flanking) had on past fires as fuel breaks. We found that regardless of past burn severity, future wildfire severity was mitigated by recent past fires.

Our third objective was to create a landscape fire simulation tool that allowed us to explore the impact of wildfires and fire management on the patterns of forest vegetation and fuels across recurrently reburned landscapes. To do this, we created an iterative GIS and fire growth modeling process 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. With our model, we were able to visualize the actual effects of prior-year fires on ignitions, fire flow on the landscape, and fire containment by fire-fire interactions. We were also able to reveal how lagged effects of time-since-fire patterns and fire weather conditions influenced the efficacy of fire-fire interactions to constrain fire growth or severity patterns. These new utilities provided us with a platform to compare different wildfire management strategies and their efficacy in constraining fire growth and severity patterns. Our results offer a unique perspective on the long-term consequences of wildfire management decisions – in particular, the implications of fire suppression decision for future wildfire event sizes and their severity patterns.

Of the four scenarios we modeled, the No Fire and Modern Suppression scenarios represented “boom and bust” landscapes, where well connected mature forests with their complex surface fuel beds were capable of supporting large fire growth and high burn severity impacts. The Partial and No Suppression scenarios revealed fine to meso-scale patch mosaics that provided markedly different options for fire managers due to the remaining effectiveness and durability of prior fire-fire interactions for constraining fire growth and burn severity. The Partial and No Suppression scenarios likewise supported more diverse habitat patchworks.

We presented research findings to managers in a series of manager workshops in north-central Washington (Wenatchee, WA), the northern Rockies (Missoula, MT and McCall ID) and interior British Columbia (Quesnel, BC). The goal of each workshop was to provide an exchange of research findings and to obtain fire manager feedback on how alternative landscape management scenarios might be used in wildfire management. Findings are also available on a project website and are being packaged for webinars and wildland fire management courses.

1. Objectives

The central objective of this study was to evaluate the effects of past wildfires on the growth, severity, and management of subsequent wildfires. We employed three study areas in the western United States and BC, Canada to assess 1) the effectiveness of past wildfires at mitigating subsequent wildfire severity and spread, and 2) the use of past wildfire mosaics in strategic and tactical fire management planning, including cost tradeoffs of fire operations under a range of fire weather scenarios.

With a combination of burn severity analysis and fire simulation modeling, we evaluated the influence of past wildfires on potential fire spread, fire severity, and management responses in subsequent wildfires. Our research addressed two of the questions of the original task statement (Influence of past wildfires on wildfire behavior, effects, and management):

1) *How do the location, size and age of past wildfires influence subsequent wildfire behavior and effects*? Specifically, are past wildfires effective as barriers to subsequent fire spread or to mitigate burn severity?

2) *How do past wildfires influence or inform management strategies for subsequent wildfires*? Specifically, how can past wildfires be used in strategic and tactical responses to large, high severity fire events?

One of our three study areas was located in the Canadian Rockies of southeastern British Columbia. In response to regional wildfires in 2003, including the 2003 Kootenay Complex fires, and more recently in the record-setting wildfire seasons of 2017 and 2018, Parks Canada and the BC Ministry of Forests have re-examined fire management planning. This project provides critical and timely analyses of the effects of past wildfires on subsequent wildfire behavior and fire management strategies in the US and Canada.

2. Background and Purpose

Across much of western North America, the incidence and severity of wildfires are increasing. Expanding area and severity are associated with a warmer climate, longer fire seasons (Flannigan et al. 2009, Jolly et al. 2015), and expanded forest area and density (Hessburg et al. 2005, 2015). Many projections of future fire hazard and area burned in fire-prone ecosystems have anticipated a doubling or quadrupling of annual wildfire area burned (McKenzie et al. 2004, Westerling et al. 2011). However, as wildfires burn more area each year, an increasing proportion of burned landscapes will reburn within past fire mosaics, and subsequent fire behavior and effects often will be modified by reduced fuel biomass and continuity of previously burned areas (Moritz et al. 2011, O'Neill et al. 1992, Peterson 2002, Parks et al 2015, McKenzie and Littell 2017). With the growing number of large wildfires and costly wildfire seasons, a better understanding of fire on fire (hereafter fire-fire) interactions and their implications for ecological effects is needed to inform science and management of fires.

Wildfires in forested landscapes with high-severity fire regimes can be large and difficult to manage. Often located in remote areas, wildfires can span large areas (> 1000 ha) and require expensive, indirect suppression. With the expansion of wildland-urban interface (WUI) communities in montane areas, high-severity wildfires increasingly contribute to the ballooning costs of firefighting (Liang et al. 2008). Large fire events are disproportionately expensive to suppress; high fuel loads and high-intensity fire behavior are significant cost and efficacy predictors (Calkin et al. 2005, Gebert et al. 2007). However, due to WUI and other valued resource concerns, opportunities for limiting direct suppression expenditures and instead managing wildfires for resource benefit are often limited.

In forested landscapes throughout western North America, the landscape patterns, density and structure of forests today could not exist without the legacy of frequent past disturbances, and the myriad interactions among disturbances on successional patterns and their related structure. Within this region, marked departures from historical fire regimes have created a fire deficit in many fire-adapted ecosystems. For example, forests that once had frequent low-severity fires are now often highly susceptible to stand-replacing, high severity fire events. However, even in areas that have had decades of fire exclusion, the legacy of past fire regimes is still often evident with large, fire-scarred thick-barked trees such as ponderosa pine (*Pinus ponderosa*), western larch (*Larix occidentalis*) and Douglas-fir (*Pseudotsuga menziesii*) now surrounded by younger, suppressed shade-tolerant trees and shrubs such as Douglas-fir, grand fir (*Abies grandis*) and white fir (*A. concolor*) (Covington et al. 1994, Veblen et al. 2000, Heyerdahl et al. 2012). Over decades of fire exclusion, mid to high-elevation forested landscapes have generally infilled with continuous, mature forest relative to historically more patchy, open landscapes composed of grasslands, recently burned shrublands, young forests and older closed-canopy forests (Hessburg et al. 2015, 2016, Perry et al. 2011).

Given that many fire-prone ecosystems have altered fire regimes due to a combination of changing climate (Westerling 2016), past fire exclusion (Hessburg et al. 2015, Prichard et al. 2017), and increased human ignitions (Balch et al. 2017), a better understanding is needed about the role of past fire mosaics on subsequent fire spread and effects. Specifically, guidance is needed to restore fire as a forest maintenance process, which has implications for wildland fire management planning, climate change adaptation, and wildlife habitat conservation. To make informed management decisions, wildland fire managers need better information on the role that landscape burn and reburn mosaics play in constraining fire spread and burn severity, and the resiliency of landscapes to future wildfires.

Our Reburn Project was motivated by a need to evaluate wildfires as one type of fuel reduction treatment and to assess the impacts of fire suppression on forested landscapes. We first assessed fire-on-fire interactions of past wildfires and subsequent large fire events (see Stevens-Rumann et al. 2016). Then, we created a landscape fire simulation tool that allowed us to explore the impact of fire management on the patterns of forest vegetation and fuels across landscapes. To do this, we created an iterative tool that uses historical ignition and weather data to evaluate potential burn mosaics compared to actual pre-wildfire landscapes under different wildfire management strategies.

3. Methods

3.1 Study areas

Each of our three study areas (**Figure 3.1**) focuses on a large fire event in mixed conifer forests. These fires stemmed from regionally severe fire years and were noteworthy for their size and severity. Study areas are within cold, upper elevation, montane lodgepole pine (*Pinus contorta*), subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engelmannii*) mixed conifer forests.

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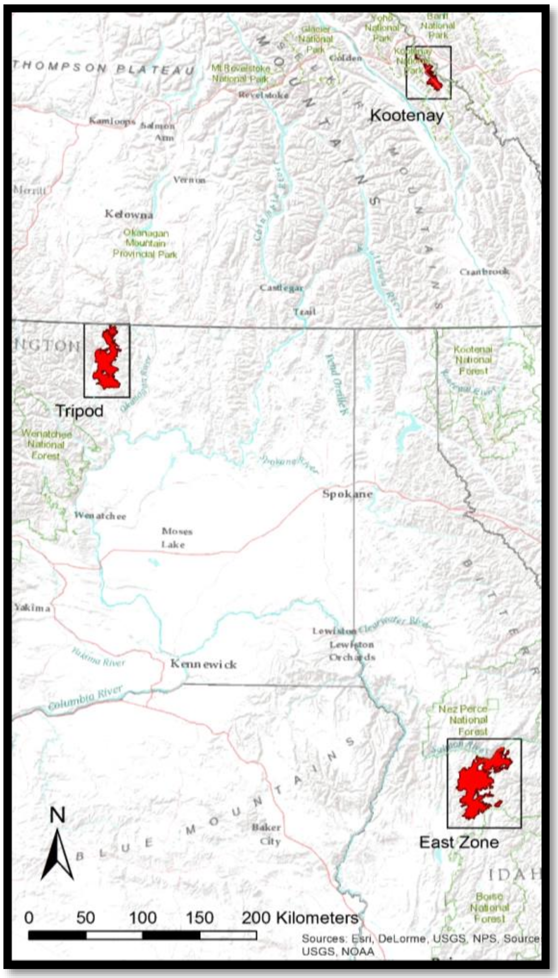

Figure 3.1 Study area locations.

Tripod

The 2006 Tripod Complex burned over 70,000 ha of the Okanogan-Wenatchee National Forest (MTBS 2010; Prichard and Kennedy 2014). Approximately 65% of the area burned at high-severity. The study area supports ponderosa pine and Douglas-fir forests in the lowest elevations, with extensive high-elevation, cold mixed conifer forests. Above these cold forests, forests yield to subalpine whitebark pine (*Pinus albicaulis*) and subalpine larch (*Larix lyallii*) parklands (Figure 3.2).

Figure 3.2: Post-fire photo of the 2006 Tripod Complex burn near Roger Lake in the foreground with regenerating forests from the 1970 Forks fire in the background.

East Zone

In 2007, the East Zone Complex fires burned over 128,000 ha on the Boise and Payette National Forests in central Idaho (MTBS 2010; Hudak et al. 2011) and was active concurrently with adjacent large fires including the 128,000-ha Cascade Complex to the south and 40,000-ha Rattlesnake Complex to the North. The East Zone Complex study area was selected because it was in the center of the two other fires and supports a wide range of forest types and elevations from subalpine forests and meadows at high elevation to lower tree line dominated by ponderosa pine woodlands (**Figure 3.3**).

Figure 3.3: Reburned area of the 1994 Porphyry South fire located within the East Zone Complex.

Kootenay

The 17,000-ha 2003 Kootenay Complex, which burned within Kootenay National Park of southeastern British Columbia, was at the time, one of the largest fire events to have occurred in the Canadian Rockies in the past century. The study area is dominated by high elevation cold mixed-conifer forests. Over 75% of the area burned at moderate to high severity. Pre-fire fuel complexes were comprised of mature mixed-conifer forests of lodgepole pine, Engelmann spruce, and subalpine fir. Regardless of the surface or crown fire driven fire behavior, a striking feature of the post-burn landscape is the nearly uniform pattern of tree stand replacement (**Figure 3.4**).

Figure 3.4: Post-fire photo of the 2003 Kootenay Complex Fire in the distance along the Vermillion River. In the foreground is a portion of the 1994 Shank fire that was subsequently reburned by the 2012 Octopus Mountain fire.

3.2 Burn Severity Analysis (Task 1)

Note: this section was published in Stevens-Rumann et al. (2016). Method and key findings are adapted from the published paper.

In Task 1, we evaluated the combined influences of prior fire burn severity, topography, vegetation conditions, and fire weather on the burn severity of four recent large fire events. The response variable was burn severity, which was represented by continuous RdNBR (relative differenced normalized burn ratio) or dNBR (differenced normalized burn ratio). Candidate predictor variables included several weather variables, the burn severity of past wildfire events (e.g., unchanged or unburned, low, moderate, and high), time since previous fire, several topographic variables, the vegetation type, and fuel characteristics (Table 3.1). We examined co-linearity between possible predictors with pairwise correlations, and excluded correlated variables ($r > 0.85$; Nash and Bradford 2001) from the same model. Simultaneous auto-regression models (SAR) were constructed in R programming language (R Development Core Team 2011) using methods similar to Prichard and Kennedy (2014) and Kennedy and Prichard (2017). We compared individual variable models using the Akaike Information Criterion (AIC; Akaike 1974), and then selected final multivariate models based on lowest AIC values. We tested multiple models and removed variables when the AIC value was not reduced by more than 50.

In a previously funded JFSP study, Prichard and Kennedy (2014) demonstrated that using a 30 m nearest neighborhood distance minimized both AIC and Moran's I, and we confirmed with Moran's I that our final models did not display autocorrelation of the residuals at this distance. Although SAR analyses define the SAR neighborhood weighted matrix by subsampling to reduce computational resources and time (Kennedy and Prichard 2017), we assigned point data information to each 30 m pixel across the entirety of each of our four study fires, including areas previously unburned. In the Cascade and East Zone Complex a spatially continuous dataset was impossible due to a failure of the Landsat 7 EMT+ scan line correction mechanism (known as SLC-off condition; Howard and Lacasse 2004). In these two wildfires, we used all available points, skipped the 150m scan line areas, and treated pixels surrounding the scan lines as true neighbors. To address the possibility that missing data skewed results of our SAR analysis, we performed a test of bias by examining the distribution of cover type and topographic variables within scan line versus other areas using RdNBR data. Our examination of pixels within and outside the scan lines showed that the distribution of canopy cover, elevation, slope, solar radiation, and topographic wetness index were nearly identical for both the Cascade and East Zone Complex fires and, therefore, that there was no evidence of bias due to scanline errors.

In addition to examining these fires as continuous study sites, across all cover types, we did two additional SAR analyses within each study fire to determine how past fires influenced burn severity within different forest types. We refer to these as "cover type models". To extract data for these analyses, we grouped our previous cover types into "low-elevation forest type" (Douglas-fir/western hemlock (*Tsuga heterophylla*), ponderosa pine, dry–mesic mixed-conifer) and a "high elevation forest type" (lodgepole pine, Engelmann spruce, subalpine fir), and ran the SAR analysis only on points that fell within each of these broad forest type classifications. Only two factors were considered in this model: time since previous fire and past burn severity.

For each of the four study fires, we used data from multiple sources to examine drivers of burn severity (Table 3.1). We assessed the impact of previous wildfires by evaluating burn severity using a continuous RdNBR map (Miller et al. 2009) of the three fires, which was obtained from the Monitoring Trends in Burn Severity (MTBS) project (Eidenshink et al. 2007). We chose RdNBR over other metrics of burn severity because it is generally a reliable predictor of field-validated burn severity (Miller et al. 2009; Prichard and Kennedy 2014), and is especially suitable for heterogeneous vegetation (Parks et al. 2015). Additionally, field-based composite burn index (CBI) values on the Tripod Complex Fire were highly correlated with RdNBR (R^2 =0.71; Prichard and Kennedy 2014).

Table 3.1: List of predictor variables used in SAR models of burn severity

Variable (units)	**Definition**
PastSev	Past burn severity; categorical RdNBR (unburned, low, moderate and high)
Edge (m)	Distance to edge of treatment
TSF	Time since fire (years since pixel last burned)
MaxTemp (C)	Maximum temperature over progression interval
AvgTemp (C)	Average temperature over progression interval
MaxGust (kph)	Maximum recorded wind speed over progression interval
AvgGust (kph)	Average wind speed over progression interval
MinRH (%)	Minimum relative humidity over progression interval
CBD	Canopy bulk density (LANDFIRE 2012)
CovType	Cover type, derived from Existing Vegetation Type (LANDFIRE 2012)
CC (%)	Canopy cover (LANDFIRE 2012)
Elev (m)	Elevation from national elevation dataset
Slope (degrees)	Slope gradient
Solar radiation (WH m^{-2})	Potential incoming solar radiation (no cloud cover)
TWI	Topographic wetness index

Variable (units)	**Definition**
TPI	Discrete classified topographic position index
Valley	Valley-like position defined from TPI
Ridgetop	Ridge-like position defined from TPI

For the Kootenay Fire, we used dNBR, which was post-processed by Kootenay National Park officials. Due to the largely homogenous cover type displayed within this burned area, dNBR was considered an appropriate proxy for RdNBR (Miller and Thode 2007). We used the MTBS data for the prior fires for three potential predictor variables. First, we converted continuous RdNBR and dNBR values for past fires into categorical variables of "unchanged or unburned", "low", "moderate", and "high" using metric-specific thresholds established by Miller and Thode (2007) to apply consistent classifications between study areas. For our analysis, categorical variables were required to have a base contrast for regression comparisons; we used unchanged or unburned as the base contrast. Second, time since fire was assigned for each pixel that experienced two or more fires since 1984. For pixels not previously burned, we assigned "100" as time since previous fire. We categorized these as "100" years since fire because burn severity data inferred from Landsat TM satellite imagery are only available after 1984 and most of these forests are known to be dominated by trees that are more than 80 years old (Schellhaas et al. 2001). For pixels that were reburned more than once (i.e., burned in three or more wildfires between 1984 and 2007), the most recent fire year was used to calculate time since previous fire. This did not occur on the Kootenay Fire and occurred on only 2% of the reburned area of the Tripod Complex Fire. On the Cascade Complex Fire, this occurred on 3% of reburned pixels, and on the East Zone Complex Fires, it occurred on 4%. To understand possible edge effects such as fire suppression and changes in fire behavior along a fires perimeter, we used a distance to edge metric calculated as the distance of each pixel to the nearest burn perimeter. Although fire management actions during wildfires likely altered fire extent and burn severity, we did not account for them directly, as the records of management actions were incomplete.

We were able to partially evaluate RdNBR accuracy in reburned areas by examining relationships between field-based CBI values and RdNBR values in reburn areas of the 2006 Tripod Complex fires. Field validation plots were established in prescribed burn areas that reburned in the Tripod Complex Fire, and most were classified as low burn severity areas as a result of the treatment effect (Prichard and Kennedy 2014). On these sites, producer's accuracy was around 40%; however, 95% of misclassification errors occurred when RdNBR values were close to the burn severity cutoff between unchanged and low, or low and moderate severity, as established by Miller and Thode (2007). Field validation did not differ from that inferred from satellite imagery by more than a single class (e.g., low severity found as moderate severity).

To examine the impact of weather on the day of burning, we acquired fire progression interval layers from the Okanogan-Wenatchee, Boise, and Payette National Forests, as well as from Kootenay National Park. Progression layers allowed us to narrow the time frame within which each pixel burned to a 10–96 h window, depending on when the frequency progression intervals were sampled from infrared imagery. We then assigned weather characteristics during each progression interval based on the date each pixel burned. We assigned maximum and average wind taken at 6.1

m above ground, maximum and average air temperature, and minimum relative humidity (RH). These data were acquired from nearby remote area weather stations (RAWS): the First Butte station for the Tripod, the Tea Pot Idaho station for the Cascade and East Zone (Western Regional Climate Center; available from http://www.raws.dri.edu/, last accessed 13 January 2015), and Vermillion weather station (courtesy of Parks Canada, Kootenay National Park). All stations were within 5 km of the nearest burned edge. From the Vermillion station, we could acquire daily mean temperatures, relative humidity, and average wind speed, and maximum and minimum values were unavailable and excluded from analysis.

Vegetation and fuels information was derived from LANDFIRE products (30 m resolution; Ryan and Opperman 2013). We used 2001 crown bulk density, fire regime group, and canopy cover data to reflect the best data for conditions prior to the three study wildfires. We also converted the 40 existing vegetation type to seven "cover type" categories, to regroup similar vegetation types. Cover types were "lodgepole pine", "ponderosa pine", "subalpine forest", "riparian", "dry–mesic mixed-conifer", "Douglas-fir/western hemlock", and "grassland and (or) shrubland". Grasslands and shrublands comprised a relatively small portion of the total study area landscapes with 8% on the Tripod, 15% on the East Zone, and 18% on the Cascade; thus, we grouped all grasslands and shrublands together for the analysis, even though conditions of these various grassland and shrubland cover types can be highly variable. We used "dry–mesic mixed-conifer" as the base contrast for burn severity comparison. Vegetation type and stand origin maps are available from Kootenay National Park, but due to the fairly uniform vegetation types and stand structures, we did not include vegetation characteristics for this model.

Evaluation of reburns as barriers to fire spread

Following the publication of these results, we performed an additional analysis to evaluate past fires as barriers relative to time since fire. For each past fire, we tabulated the percent of pixels reburned in the subsequent fire and compiled a summary of percent area reburned and likely fire spread into the unit based on progression intervals.

3.3 Reburn Simulation Modeling (Task 2)

The Reburn simulation modeling task was designed to create a landscape fire simulation tool that allowed us to explore the impact of wildfires and fire management on the patterns of forest vegetation and fuels across recurrently reburned landscapes. To do this, we created an iterative GIS and fire growth modeling process 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. Vegetation and fuels are modeled on an annual time step using a State and Transition Model that has pathways to reflect low-, moderate- and high severity effects on forest vegetation and tracks forest growth and fuel accumulations over time.

State and Transition Model Development

STMs were developed to represent major vegetation pathways within mixed conifer zones of the East Zone, Kootenay and Tripod landscapes, and the likelihood of low, moderate, and high severity burns. Based on site visits and consultations with local area managers, we developed separate models to represent the high-elevation subalpine forest of the Kootenay landscape with longer successional pathways. Although distributions of vegetation vary between the East Zone and Tripod landscapes, the two study areas share common vegetation types and were represented with the same STMs, but with differing rates of fuel and canopy succession, which reflected greater productivity in the East Zone landscape. Using structural characteristics summarized for representative subbasins within the Interior Columbia River Basin Ecosystem Management Project (Hessburg et al. 1999, 2000), we also assigned forest canopy layers, tree sizes, shrubland characteristics (cover and height), and herbland characteristics (cover and height). Based on assigned vegetation type and structural attributes, these STMs can be used later to provide wildlife habitat suitability conditions for certain species, and an approximate estimate of aboveground carbon stores based on assigned vegetation type and structural attributes.

The STMs trace successional vegetation pathways as they interact with fire of variable timing and severity. Each state provides a vegetation structural class (O'Hara et al. 1996), a time step between stages (the succession clock), and surface and canopy fuel assignments including surface fire behavior fuel model (Anderson 1982, Scott and Burgan 2005), canopy cover (CC, %), canopy base height (CBH, m), and canopy bulk density (CBD, kg m^{-3}). State assignments and pathways were constructed using a combination of all existing datasets and expert opinion. Early successional pathways and the time that burned sites remain as barriers to fire spread were informed by past studies of fire-fire interactions (Prichard and Kennedy 2014, Stevens-Rumann et al. 2016) and by field visits, in the case of the Kootenay Study area.

Rates of forest succession in each STM pathway were independently calibrated using the Forest Vegetation Simulator (FVS, https://www.fs.fed.us/fvs). We used tree list data from FIA plots within the Okanogan and central Idaho study areas to run forest successional development simulations in FVS. Simulations included the structural class (*keyword* StrClass) and canopy fuels (*keywords* CanCalc, CanFProf) of the Fire and Fuels Extension. FVS simulations were run for 250 years and used to validate and calibrate successional time steps for all transitions in each STM pathway. For high elevation Engelmann spruce—subalpine fir (ESSF) stands, stand structural class definitions were adjusted to account for potentially lower stocking in stand initiation (changed from a minimum of 200 to 100 trees per acre) and lower tree diameter (transition diameter threshold was changed from 25 inches to 15 inches). Because the Kootenay study area is in Canada, a proxy dataset from high elevation forests in the northern Rockies of Montana was developed to represent the Kootenay pathways.

We used Surface and Tree Mortality modules within BehavePlus (Andrews et al. 2008) to predict flame length and probability of tree mortality across a range of weather scenarios--representing early season, mid-season and late-season fire weather for each study area, based on 30-year climate summaries (Table 3.2). From our BehavePlus predictions, we then developed a set of flame length thresholds that could be used to relate predicted flame length to burn severity. Following severity definitions of Perry et al. (2011), high severity was defined as 70-100% tree mortality, moderate severity as 20-70% tree mortality, and low severity as <20% mortality. In this paper, we use the term *moderate severity* to represent the middle range of severity for each state. The term *mixed severity* is applied to larger spatial scales and represents the range of low-, moderate- and high-severity fires at work within these STMs (Perry et al. 2011).

Surface and canopy fuel assignments were made for each state. The assignment of surface fire behavior fuel model for each pathway was informed by local fire managers, field observation of state examples, and published photo series. Canopy fuel assignments were informed by FIA data and FVS runs to assign canopy cover, height, base height and bulk density to each state. To model the percent tree mortality for each state, we chose a representative tree species for the state and assigned a diameter that coincided with the mid-point of the structure stage of the state.

In addition to fuel assignments for fire behavior modeling, we also constructed fuelbeds to represent each state within the Fuel Characteristics Classification System (FCCS, Ottmar et al. 2007). The FCCS is a software application that catalogues 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) and subcategory. Fuelbeds were constructed based on reference fuelbeds within FCCS that generally represent the major vegetation types, including low elevation mixed conifer dominated by Douglas-fir and ponderosa pine and high elevation ESSF-LP (lodgepole pine). Additional reference datasets included natural fuels photo series, activity photo series and field datasets (e.g., https://www.fs.fed.us/pnw/fera/research/fuels/photo_series). Based on previous work constructing FCCS fuelbeds to represent forest successional pathways, disturbance agents and management activities, a chronosequence approach using existing plot data is not possible due to high site-to-site variance, and in this case, reference sites are not available to represent all of the pathways and states in our models of the historical mixed severity fire regime. The FCCS fuelbeds we developed for this exercise were informed as much as possible from reference data, but relied on expert opinion for logical transitions between states and pathways.

Base Landscape Development

The LANDFIRE 2012 biophysical settings (BpS) raster was used to spatially allocate pathway groups across the study area (https://www.landfire.gov/bps.php). These data approximated the vegetation that may have been present prior to Euro-American settlement given current biophysical conditions under an historical disturbance regime (Rollins 2009). We used the BpS group level of classification to assign each cell to one of snow/ice, barren, water, peatland, sparse, grassland, shrubland, conifer, hardwood, or riparian classes. Non-forest types were not assigned to a pathway group, had no succession clock, and, if burned, reverted back to their associated non-forest type the year following a fire. Cell membership within a pathway group stayed constant across the simulation. The conifer BpS group was assigned one of dry-mixed, moist-mixed, cold-dry, or cold-moist based on topographic position, aspect, and elevation. (**Figure 3.5**).

Reburn Simulation Model

Fire simulation modeling –We developed a geospatial fire simulation modeling tool that iteratively models fire spread using fire ignition, weather inputs and a base landscape that is updated on an annual time step to represent vegetation and fuel succession and responses to fire (**Figure 3.6**). Vegetation and fire dynamics are modeled with STMs to reflect low-, moderate- and high severity effects on forest vegetation and forest and fuel succession over time.

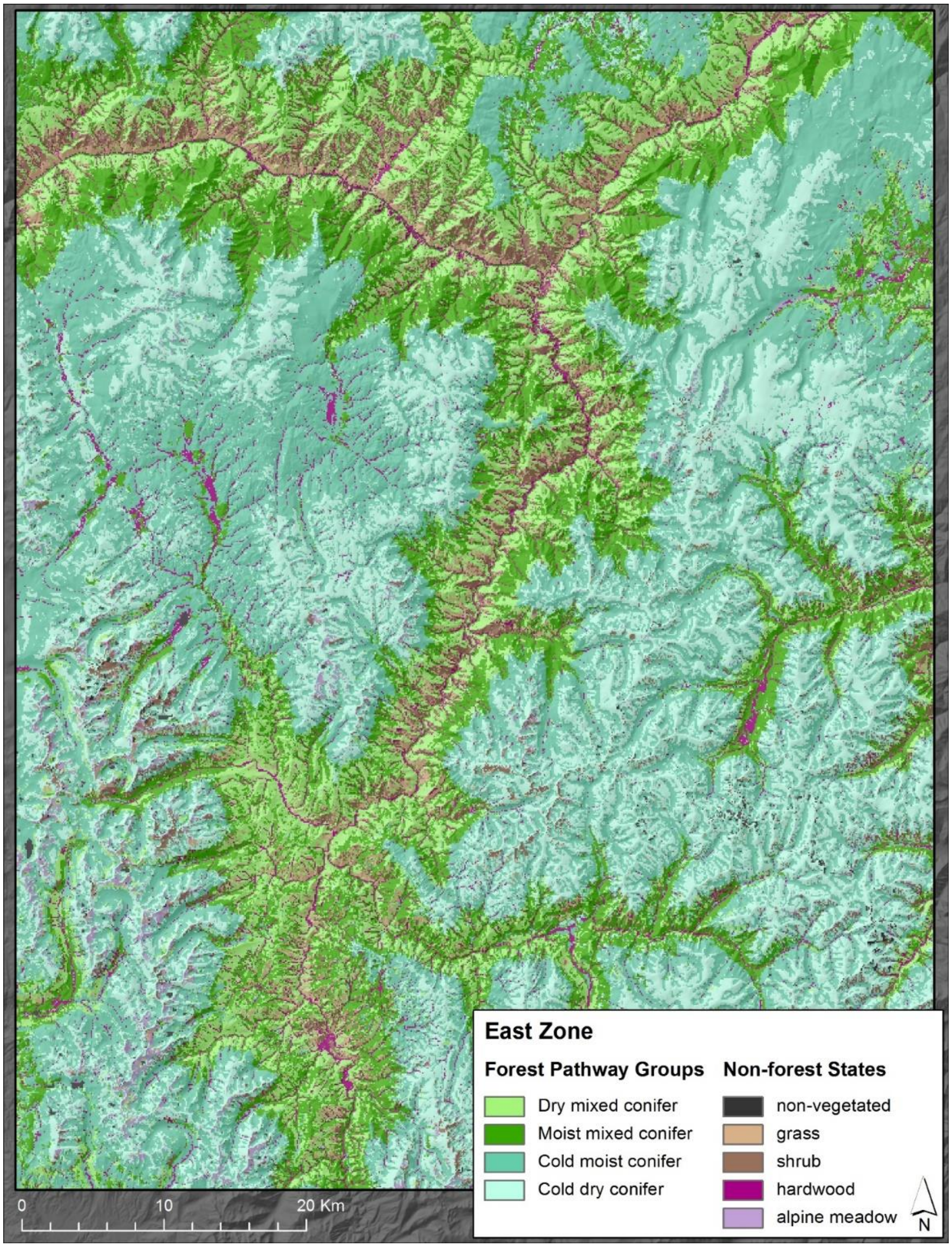

Figure 3.5: Sample base map of State and Transition Model assignments for the East Zone study area. Forest states represent the four STM pathways. Non-forest states are represented by single state values that do not change following fire.

The landscape fire model, FSPro, was selected to simulate expected wildfire spread and intensity (flame length) given observed georeferenced ignition points, daily weather stream data, and a digital elevation model. FSPro is a probabilistic model that predicts fire growth across landscapes to inform long-term decision making (Finney et al. 2011). Fires are simulated in FSPro using the Minimum Travel Time (MTT; Finney 2002) algorithm, which spreads fire from an ignition point across a grid of regular spaced nodes by identifying the node with shortest-in-time straight-line travel path among lattice nodes. This algorithm has been shown to recreate realistic fire growth patterns, spread rates, and flame lengths (Finney 2002, Finney et al. 2011).

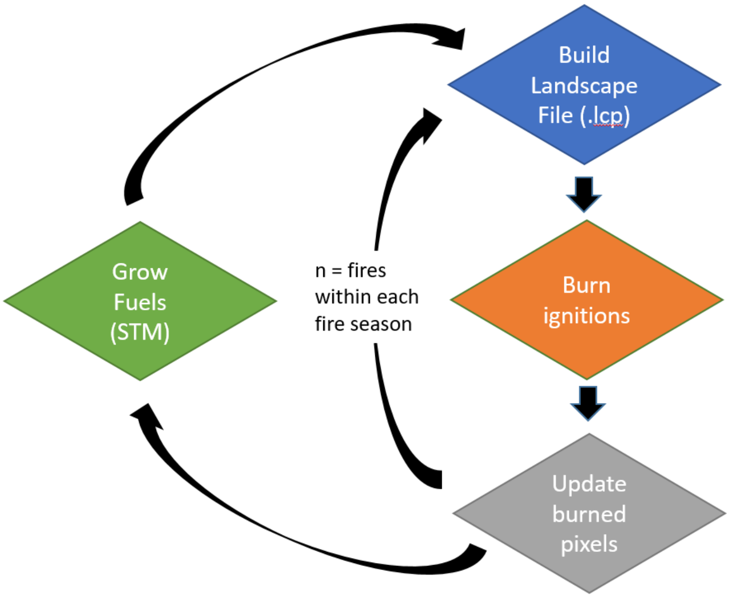

Figure 3.6: System diagram of the Reburn simulation tool. Fires are modeled within each fire season, and base landscapes are updated on an annual time step to represent fuel and vegetation succession and responses to recent fires.

FSPro was chosen because (1) it allows for daily ERC (energy release component, Cohen and Deeming 1985), wind speed and wind direction to vary across the burn period, (2) specification of ERC threshold values is possible to predetermine the length of the burn period, (3) it is available as a command-line version and could be integrated into a geospatial modeling framework, (4) unlike FARSITE, which is meant for near-term (1-5 day) fire spread predictions, FSPro is designed for longer term assessments of fire spread and severity (>5 days) and (5) FSPro is used within the Wildland Fire Decision Support System by wildfire managers for strategic and tactical fire management decision making. FSPro is typically used during a wildfire incident to predict--across a large landscape--the future probability of burning for all raster cells. As such, the model is generally run over thousands of iterations under various predicted weather streams that are drawn from historical weather data supplied by the user. However, our process incorporated historical daily weather data, so we did not need to predict weather. Therefore, weather conditions following an ignition were predetermined, requiring only a single iteration of FSPro for a given ignition.

Inputs into our fire simulation model included a time series of daily ERC values, wind direction and speed, and a series of fuel moisture bins based on percentile weather classes (see *Weather data*). For each fire growth day, FSPro models fire spread and flame lengths under the appropriate fuel moisture bin based on the daily ERC, and on the daily wind speed and direction. Fuel moisture bins included information on daily 1-, 10-, 100-hour dead fuel moistures, live herbaceous and live woody fuel moistures, daily burn period (minutes), and spotting probability

(Table 3.2 – Example fuel moisture bins). Spotting was disabled in the current assessment because of its contribution to unrealistically large fire growth. Using the historical weather data, fuel moisture inputs were calculated (see *Weather data*) separately for fires that ignited during spring, summer, and autumn. This allowed for temporal variation in the percentile fuel moistures and burn period lengths across a year. For each season, a time series of daily ERC values estimated at 1300 hr was created from 1940-2006, and fuel moistures were calculated as the average fuel moisture for each time-lag fuel class, for each percentile ERC bin.

A spatial landscape file (LCP file) was created to input raster-based maps of fuels and topography including elevation, slope-aspect, slope (%), fire behavior fuel model, canopy cover (%), crown bulk density (kg m^{-3}), canopy base height (m), tree height (m), and latitude (non-spatial). All raster data were at 90-m resolution. We selected the Scott and Reinhardt (2001) crown fire model because it resulted in much less crown fire compared to the alternative Finney crown fire model (Finney 1998).

Ignition data – For the 2006 Tripod fire, ignition data came from the Region 6 fire ignition dataset (Brian Maier, USDA Forest Service, pers. comm.), which included information on ignition location and year of ignition for fires $\geq$1940. The data, however, did not include reliable Julian dates or information on the cause of each fire (i.e., natural or human ignition source). We assigned a likely Julian date for each fire using the Federal Fire Occurrence Database (https://wildfire.cr.usgs.gov/firehistory/data.html), which includes data on the location, cause, year, and Julian date of wildfire ignitions across the United States for fires that burned between 1980 and 2010. From these data we developed a probability density function to randomly draw Julian dates based on the distribution specific to each study area. If an ignition fell on a day with an ERC <55, then the Julian date was shifted to the closest day with an ERC above the threshold.

Weather data –We used daily weather data from the VIC (Variable Infiltration Capacity[1]) model (Livneh et al. 2013). These data were selected because (1) they spanned the temporal record of our wildfire ignition database, (2) they spanned the geographic extent of all three study sites, and (3) they were spatially gridded data, which allowed us to select from many individual VIC locations within the study areas. RAWS station data were not used because according to many fire behavior analysts, their placement is often not representative of fire weather conditions and often have incomplete records of inconsistent quality. Data included 3-hourly time step precipitation, temperature, relative humidity, solar radiation, and wind speed for the years 1915-2011. Weather streams were derived from ~20,000 NOAA Cooperative Observer stations at a spatial resolution of 1/16th degrees latitude/longitude. From these data we constructed a FW13 file, a common weather observation data transfer format used in desktop applications such as FireFamily Plus (Bradshaw and McCormick 2000). We submitted the VIC weather data to FireFamily Plus to calculate ERC, which is a required input of FSPro.

From initial testing it was determined that the wind speed and direction data were not representative of typical fire weather conditions (Brian Maier, personal communication), and therefore we opted to use wind data collected by a neighboring RAWS (Remote Automated Weather Station) station (Table 3.3). Wind direction and speed data were collected from RAWS stations from

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

1998 to 2015 and included winds recorded between 10:00 AM and 8:00 PM from July 1 to September 30. A wind frequency matrix was created from these data (Table 3.4), which provided frequencies of specific wind direction and speed combinations. This matrix was used to assign a wind speed and direction to each ignition for each fire growth day.

Table 3.2. Within-season average fuel moistures calculated across percentile ERC bins for the 2006 Tripod study area. Seasons are: Spring (March 31 – May 31), Summer (June 1 – September 15), and Autumn (September 16 – November 1).

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

Table 3.3. Description of RAWS stations (US study areas only) used for wind speed and direction data.

Study fire	Station name	NWS ID	Latitude	Longitude	Elevation (ft)
2006 Tripod fire	First Butte	452006	48° 37' 02"	120° 06' 27"	5500
2006 East Zone complex	Tea Pot	101220	44° 54' 16"	115° 44' 15"	5152

Table 3.4. Wind matrix for the First Butte RAWS station used to approximate frequency of wind direction and speed combinations for the 2006 Tripod Fire.

MPH	N (360)	NE (45)	E (90)	SE (135)	S (180)	SW (225)	W (270)	NW (315)
5	1.82	1.42	1.78	2.88	11.45	11.51	5.87	3.1
10	0.99	0.41	0.97	2.31	9.17	6.41	3.88	4.21
15	0.75	0.2	0.49	1.31	6.25	4.99	2.66	3.21
20	0.34	0.04	0.17	0.41	1.41	0.8	0.61	1.14
25	0.13	0.01	0.04	0.08	0.23	0.09	0.09	0.4
30	0.04	0.01	0	0.03	0.03	0.01	0.03	0.15
35	0.02	0	0	0.01	0.01	0.01	0	0.03
40	0	0	0	0	0	0	0	0.01

Model workflow

We established a workflow protocol that remained consistent across the three study areas. Differences in the sources of data and specific STMs used for each study varied among sites to best represent the individual study systems.

Model calibration – Based on the model workflow outlined below, we conducted several initial runs of the model to assess its behavior. Wildfire event size distributions were compared against those created from the MTBS (Monitoring Trends in Burn Severity, Eidenshink et al. 2007), for fires that intersected the study area between 1984 and 2013. We used historical range of variability (HRV) estimates from the midscale assessment of the Interior Columbia River Basin study (Hessburg et al. 1999) to compare the percentage composition of structural classes across Pathway Groups (i.e., dry-, moist-, cold- mixed conifer forest).

Initial landscape spin up – To approximate the landscape patterns present in the early 20th century prior to large-scale successful fire suppression operations, we ran a variant of our model for 1300 years. For this version of the model, we allowed only natural lightning ignitions and no fire suppression activities. For each simulation year, we drew a random year between 1940 and 2005, which determined the VIC ERC stream data for the year. The number of fire ignitions for that year were drawn from a probability density function developed from the Federal Fire database and included only lightning-caused fires. These data were also used to develop a probability distribution of Julian days for known lightning-caused ignitions, which was used to assign each ignition a random Julian day. The spatial location of each annual ignition was determined using a probability density function developed from the U.S. National Lightning Detection Network Database (NLDN, Cummins et al. 1998) from 1989 to 2013. For each fire, we determined if the ignition occurred on a burnable substrate, and if the ERC for that day exceeded the value of 55. If one of those criteria was not met, the model moved on to the next fire. For all other fires, we pulled the VIC ERC stream data for that year and Julian date. We determined the number of fire growth days where the fire was extinguished if two consecutive days recorded ERC <55, or after a maximum of 14 days. For each fire growth day, a random wind speed and direction were drawn from a wind probability matrix. The ERC data, along with the digital terrain model, fire behavior fuel model (FBFM) raster, and additional wind data were submitted to the FSPro simulation model to spread the fire for the predetermined number of days. After each fire burned, all burned cells were converted to NB9 (non-burnable) for the remainder of the year. At the conclusion of each fire season, we took the flame length calculated by FSPro for each burned pixel and converted that flame length to fire severity based on the pre-fire canopy base height and surface fuel state. We then updated the vegetation and fuel map (state map) to the new state value.

The spin up simulation began with a base landscape for which each pixel was assigned to the initial post-fire bare ground state of the associated STM, and the succession clock moved forward until fires began influencing their dynamics. Once calibrated, we determined that these simulations required at least a 300 year burn-in period such that the effect of the initial NB9 landscape was eliminated from the model dynamics.

Evaluation of Fire Management Scenarios

We tested four fire suppression scenarios using our Reburn Simulation Tool:

Complete absence of fire (no fire) - In this scenario, we evaluated how a complete absence of fires would alter the landscape mosaic.

Modern Suppression - The modern fire suppression scenario was designed to represent contemporary wildland fire management in which only the fires that escape suppression (the 2-3% of fires of that burn under extreme 97th percentile fire weather) were allowed to burn.

Partial Suppression - The partial suppression scenario allowed for managed wildfires in the late-summer and fall fire seasons and escaped wildfires.

No suppression – All fires allowed to burn.

To address the many uncertainties involved with fire-spread modeling and historical weather records, we ran each management scenario 25 times to evaluate how patterns might change based on random draws from wind and weather scenarios. We began simulating fires at the start of our historical fire records (e.g., 1925, 1940 and 1956 for the Kootenay, Tripod and East Zone study areas, respectively). From the initial spin up simulation, we selected a representative simulation year as an initial landscape for our scenarios. We evaluated all years of the initial spin up landscape (i.e., years 300 – 1300) based on their composition of structural states compared to the HRV estimates. Those with structural states within the 80th percentile of the HRV received higher scores and were selected as the initial landscape.

For the years 1940 - 2005, we identified the number of fires recorded in the historical record that burned in that year within our study sites. For each ignition, we drew a series of Julian days from a probability distribution of days with known historical ignitions and assigned each annual ignition a Julian date. Fires were then run similar to the initial spin up. Criteria for fire end dates were related to the daily ERC values following an ignition, and the fire suppression scenario for the run (see *Fire suppression scenario*).

We then repeated the entire >60 year simulation 25 times for each fire suppression scenario to identify the range of vegetation conditions associated with each. Variations across iterations could arise from: (1) the random draws on Julian day from a probability distribution of recorded historical ignition days for each ignition (see *Ignition data*), and (2) the random draw of wind speed and direction for each fire growth day (see *Weather data*).

4. Results and Discussion

The following sections summarize results and key findings for the Reburn Project and are organized by publication.

4.1 Stevens-Rumann, C.S., Prichard, S.J., and Morgan, P. 2014. The Effect of Previous Wildfires on Subsequent Wildfire Behavior and Post Wildfire Recovery. Northern Rockies Fire Science Network Science Review No. 1.

https://www.nrfirescience.org/sites/default/files/NRFSNSciReview1_RepeatFires.pdf

We conducted a literature review on fire-on-fire interactions and fire-vegetation dynamics in the western United States. We found that past wildfires tended to decrease the severity of subsequent wildfires and often mitigate the amount of area burned. The effectiveness of past fires as a fuel treatment in semi-arid forests of the western US was generally about 20 years. We also identified a number of key areas for additional research including (1) the need to develop a consistent set of metrics to evaluate the effect of past fires on subsequent fire spread and severity, (2) estimates of the potential duration of treatment effectiveness may be limited by the period of available Landsat TM imagery after 1984, and (3) geographic variation in vegetation type and fire weather can strongly influence fire-on-fire interactions, and the complexity of these interactions warrants further study. Finally, we need to better understand the potential consequences of climate change on fire-on-fire interactions – specifically on how warmer and drier summers may influence future fire spread, burn severity, or post-wildfire vegetation recovery.

4.1 Stevens-Rumann, C.S., Prichard, S.J., Strand, E.K., Morgan, P. 2016. Prior wildfires influence burn severity of subsequent large fires. Canadian Journal of Forest Research 46 (11): 1375-1385. DOI: 10.1139/cjfr-2016-0185.

https://www.researchgate.net/publication/308795672_Prior_wildfires_influence_burn_severity_of_subsequent_large_fires

In this study, we evaluated how past fires and other variables including landform, vegetation and weather influenced burn severity in three large wildfire events: the 2003 Kootenay Complex fires in southeastern British Columbia, the 2006 Tripod Complex in north-central Washington State, and the 2007 East Zone Complex in central Idaho. Although the influence of past burn severity varied by study region, past fires had significantly lower burn severity than surrounding areas (Table 4.1). In the Tripod and Kootenay study areas, past burn severity was a strong predictor of subsequent burn severity with the highest reductions in severity in pixels that previously burned in high severity fire events and lowest reductions in pixels that previously burned in low severity fire. However, in the East Zone and Cascade areas, areas that had previously burned in low severity fire events actually had the highest reduction in reburn severity. Our findings of lower burn severity following high severity fire is in contrast to recent studies in other ecosystems including the Sierra Nevada (Collins et al. 2007, 2009) northern Rockies and southwestern United States (Holden et al. 2010, Parks et al. 2014). Explanations for this difference may be in part due to low productivity and lack of flammable shrub fields in the Tripod and Kootenay landscapes. Another possible explanation is that our study areas were located outside of wilderness areas, and fire suppression operations may have been used and effectively reduced spread of wildfires into past burn areas.

Across all study areas, final models of burn severity included past fire effects (severity and distance from edge), weather, vegetation, and landform variables (Table 4.1). Burn severity was related to fire weather, broadly summarized by progression interval, and suggest that fires burn with higher severity on extreme weather days associated with high temperatures and low relative humidity. Vegetation was a strong predictor of burn severity with higher burn severity in dense, closed canopy mixed conifer forests than low-elevation, more open ponderosa pine and moist riparian forest types. Burn severity was also strongly related to landform with a trend toward higher severity at higher elevations. Burn severity was generally higher on steep slopes and lower on valley bottoms. Patterns of severity across landform may be related to patterns of localized wind flow that facilitate more intense fire behavior on steep slopes and less within valley bottoms (Finney and McAllister 2011).

Table 4.1: Final SAR model results by study area.

Model	Predictor variables	N	R^2	AIC
Cascade	CC, CovType, Edge, MaxGust, MaxTemp, PastSev, Slope, TSF, Valley	975,414	0.77	13,736,440
EastZone	CovType, Edge, Elev, MaxGust, MaxTemp, PastSev, TWI, Valley	905,805	0.73	12,705,742
Kootenay	AvgTemp, Edge, Slope, PastSev	88,272	0.90	1,080,976
Tripod	CC, CovType, Edge, Elev, MaxTemp, PastSev, Slope, Valley	326,551	0.92	4,884,497

Additional Results (after Stevens-Rumann 2016 was published)

Past fires were often barriers to fire spread for up to 5-7 years post fire in the East Zone and Tripod study areas and only up to 2-3 years in the Kootenay study area. Trends in percent area reburned and time since fire (TSF) are complicated with a mixture of reburn potential in past fires with TSF < 7 years followed by a trend of increasing area burned with TSF (**Figure 4.1**). Burn severity generally increased with time since fire, suggesting that reductions in surface fuels are gradually diminished as vegetation recovers, and live and dead fuels accumulate in the years following fires.

The Cascade and East Zone fires interacted with a number of very recent fires that had occurred in 2005 and 2006. Of the 16 fires that burned within 1 and 2 years of the 2007 wildfires, three past fires had substantial areas of reburn. By subjectively evaluating wind direction and fire progression intervals, two of these past fires appeared to have been reburned in a head fire under strong winds. The remaining 13 burns were mostly barriers to fire spread with minor reburns along past fire edges.

Recent past fires in the Tripod study area had mixed results with small past burns (<200 ha in size) almost completely reburning and large past fires with very little reburn area (Table 4.2). Of the small burns that mostly reburned, only one likely burned in a head fire.

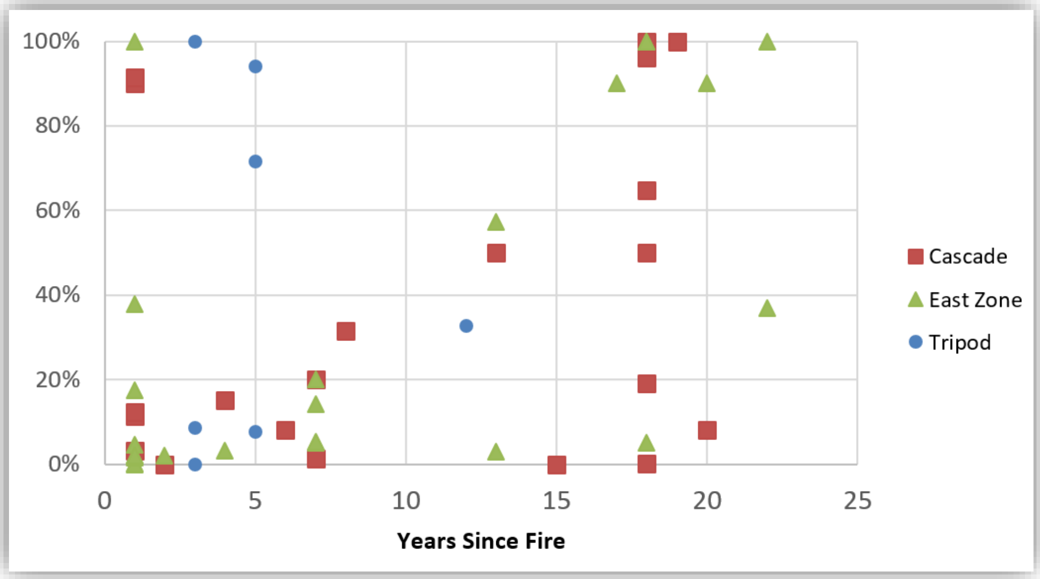

Figure 4.1: Percent area reburned in the Cascade, East Zone and Tripod Complex fires.

Table 4.2: Past fires and percent area reburned in the Cascade, East Zone and Tripod fires. Fire type entering the past fire was reconstructed from patterns of fire progression and wind records and include flanking (flank), Heading (head) and mixed flanking/heading fires.

	Past fire date	Time since fire	Area (ha)	Percent reburned	Likely fire interaction
Cascade Complex					
Boundary Complex	2006	1	6413	3%	Flank
Burnt	2006	1	891	90%	Unknown
SF Complex Bishop Creek	2006	1	1760	91%	Head
SF Complex Cougar	2006	1	11303	11%	Flank
Summit Lake	2006	1	1005	12%	Flank
Frank Church WFU (Missouri Ridge)	2005	2	2655	0%	Unknown
South Fork	2003	4	2577	15%	Flank
Snowshoe	2001	6	9504	8%	Flank
Salmon Challis Wilderness Complex (Little Pistol)	2000	7	21768	1%	Flank
Yellow Pine Complex	2000	7	0	20%	Flank
Soldier	1999	8	1050	31%	Mixed
Thunderbolt	1994	13	10544	50%	Mixed
Camp Creek	1992	15	582	0%	Unknown
Bear Creek	1989	18	2253	65%	Mixed
Dollar Creek	1989	18	4079	50%	Mixed
Horn Creek	1989	18	1007	96%	Head
Lunch Creek	1989	18	3012	19%	Mixed
Needles South	1989	18	1309	0%	Flank
Yellow Jacket III	1989	18	554	100%	Unknown
Riordan Creek	1988	19	1006	100%	Unknown

	Past fire date	Time since fire	Area (ha)	Percent reburned	Likely fire interaction
Deadwood	1987	20	23088	8%	Flank
East Zone					
Lick Creek WFU	2006	1	566	0%	Unknown
South Fork Complex (Cougar)	2006	1	0	2%	Flank
South Fork Complex (Krassel)	2006	1	421	100%	Head
South Fork Complex (Phoebe)	2006	1	686	38%	Flank
South Fork Complex (Sheepcreek WFU)	2006	1	848	5%	Flank
South Fork Complex (Tailholt Creek)	2006	1	1695	18%	Flank
South Fork Complex (Rainbow)	2006	1	1284	0%	Flank
South Fork Complex (Twin Lakes)	2006	1	486	2%	Flank
South Fork Complex (Van Meter)	2006	1	0	2%	Flank
Frank Church WFU (W Fork and Joe)	2005	2	9864	2%	Unknown
North Fork Lick	2003	4	934	3%	Flank
Burgdorf Junction	2000	7	27229	14%	Mixed
CK	2000	7	1016	20%	Unknown
Flossie Complex	2000	7	36669	5%	Unknown
Yellow Pine	2000	7	4747	5%	Flank
Corral Creek - Blackwell Complex	1994	13	56697	3%	Flank
Porphyry South	1994	13	52548	57%	Mixed
Chamberlain	1990	17	1383	90%	Unknown
Game Creek	1989	18	1247	5%	Mixed
Steamboat	1989	18	654	100%	Head
Whang Doodle	1989	18	2746	100%	Head
Cove	1987	20	2566	90%	Unknown
Boise Bar	1985	22	2081	100%	Unknown
Savage Creek	1985	22	5680	37%	Mixed
Kootenay					
Shank	2001	3	3487	10%	Burnout
Vermillion Pass Fire	1968	35	1579	80%	Burnout
Tripod					
Bottle Springs	2003	3	69	100%	Head
Isabel	2003	3	2328	9%	Flank
Long swamp	2001	5	161	72%	Flank
Thirtymile	2001	5	3691	8%	Flank
Windy Peak	2001	5	168	94%	Flank
Thunder	1994	12	4338	33%	Mixed
Farewell	2003	3	31341	0%	Flank

4.3 Prichard, S.J., Stevens-Rumann, C.S., Hessburg, P. 2017. Tamm Review: Shifting global fire regimes: lessons from reburns and research needs. Forest Ecology and Management 396: 217-233.

https://www.fs.fed.us/pnw/pubs/journals/pnw_2017_prichard001.pdf

In this invited Tamm review, we synthesized published studies on changing fire regimes and evidence of the impact of past fires on subsequent fire behavior and severity. The review summarized what is known about the influence of past fires as barriers or mitigating burn severity and the duration of this effect. The review revealed discrepancies in the number and quality of studies on fire and vegetation dynamics across the world with the most research in Australian eucalypt forest and savannas and in North America. Based on the importance of feedbacks of fire and vegetation to global carbon fluxes and the increased incidence of wildfires in the majority of the world's major biomes, further studies of fire and vegetation dynamics in southeast Asia, African savannas, China and boreal forests in Eurasia are recommended. One of the conclusions of this literature review was that with warming climate, climate-fuel relationships will likely shift in many ecosystems (**Figure 4.2**). Specifically, in productive, moist ecosystems, fuel moistures may currently limit fire growth. However, warmer drier summers may make these systems more likely to burn. In contrast some frequent fire systems may actually experience a decline in fire occurrence due to more arid conditions and less available fuel to burn. We concluded that traditional fire knowledge exists in many fire-adapted ecosystems and may provide guidance and incentives for more actively using fire to mitigate future fire severity.

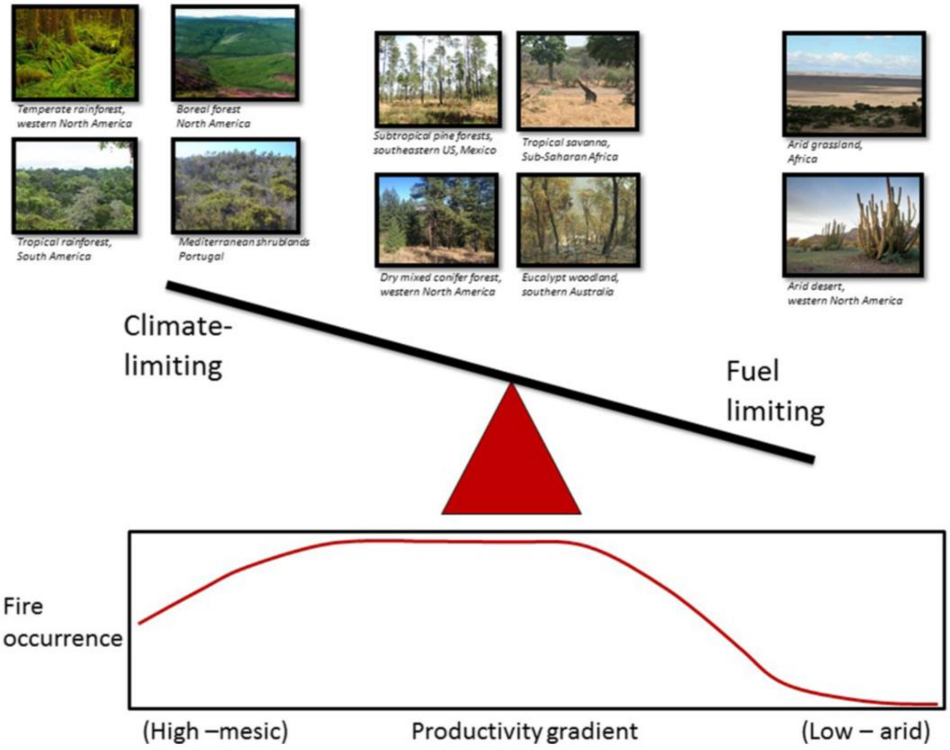

Figure 4.2: Conceptual diagram of climate- and fuel-limits on fire regimes, adapted from Krawchuk and Moritz (2011). At the moist end of the productivity gradient, mesic climates support high biomass accumulations, and fires occur during fire weather events associated with prolonged drought and/or fire weather. At the dry end of the productivity gradient, fuels are almost always available to burn but fires are constrained by lack of fuel connectivity. Spanning the middle of the gradient are ecosystem types that are strongly influenced by fuels and climate; fires are generally frequent in these systems and strongly regulate spatial patterns and types of vegetation.

4.4 Prichard, S.J., Gray, R.W., Salter, R.B., Hessburg, P.F. and Povak, N.A. In prep. Fire, fuel and vegetation dynamics – modeling wildfire and fuel succession in fire-prone landscapes. Part I: state and transition models.

Globally, the incidence of fire is increasing and is associated with a warmer climate and longer fire seasons (Flannigan et al. 2009, Jolly et al. 2015). Many projections of future fire hazard and area burned in fire-prone ecosystems have anticipated a doubling or even quadrupling of annual wildfire area burned (McKenzie et al. 2004, Westerling et al. 2011). However, as wildfires burn more area each year, an increasing proportion of burned landscapes will reburn within past fire mosaics, and subsequent fire behavior and effects often will be modified by reduced fuel biomass and continuity of previously burned areas (Parks et al 2015, McKenzie and Littell 2018). The spatial distribution of fire starts either from lightning or human ignitions is far from uniform, and areas with frequent fire starts can contribute to the concentration of reburned areas (Bartlein et al. 2008, Park et al. 2012). Another complication is that warmer and drier climatic conditions in arid landscape may actually lead to reduced productivity and continuity of fuels, translating into decreases in area burned (Bradstock 2010, Krawchuck and Moritz 2011). Given that many fire-prone ecosystems have altered fire regimes due to a combination of changing climate (Westerling et al. 2016), past fire exclusion (Hessburg et al. 2015, Prichard et al. 2017) and increased human ignitions (Balch et al. 2017), a better understanding is needed about the role of past fire mosaics on subsequent fire spread and effects and implications for wildland fire management planning, climate change adaptation and wildlife habitat conservation.

As part of a study on burn mosaics and their effect on subsequent wildfires, we developed a series of STMs to represent vegetation, fuels and fire dynamics in mixed conifer forests of western North America. The central objective of our study was to evaluate how fire exclusion has contributed to altered vegetation and fuel patterns and to evaluate hypothetical landscapes under comparative fire management strategies. We focused on three large and mostly stand-replacing fire events, located in north-central Washington, central Idaho and southeastern British Columbia, that had a legacy of fire exclusion. A key motivation for the study was how many recorded fire starts were successfully suppressed in each study area prior to the large fire event. These STMs were then used to evaluate departures associated with fire management strategies, including modern fire suppression, partial fire suppression and no suppression alternatives (see sections 4.5 and 4.6). The motivation of this study was to create a system to model vegetation and fire dynamics in western US and Canada, but the STMs have many potential applications, including translation to early and late-successional wildlife habitat, carbon stores and wildland fire emissions evaluations.

Within each of the STMs, states are populated with canopy and surface fuel inputs that can be used in operational fire behavior models that are commonly used by wildland fire managers within the Wildland Fire Decision Support System (https://wfdss.usgs.gov/wfdss/WFDSS_Home.shtml). Without a comprehensive dataset of vegetation and fuels following the complex pathways represented in these STMs, we relied on a combination of field data, FVS simulations and expert opinion based on manager input and field observations. These STMs offer a simplified but realistic representation of the multiple states that could be supported by mixed-severity fire. An online guide to the STM pathways and associated look up tables is available on the Reburn Project website at: https://depts.washington.edu/nwfire/reburn.

Summary of STM Pathways

The Cold Dry Conifer pathway (**Figures 4.3, 4.4**) represents fire and fuel dynamics of dry-site, high elevation Engelmann spruce, subalpine fir and lodgepole pine forests (ESSF-LP) generally located on exposed ridges and slopes with southern or western exposures.

The Cold Moist Conifer (CMC) STM represents similar fire and fuel dynamics in moister, more highly productive high elevation ESSF-LP forests. For example, due to more rapid vegetation change, recently burned sites remain barriers to fire for only 10 years and can then support subsequent fires.

The Dry Mixed Conifer (DMC) STM models vegetation and fire pathways on drier biophysical settings within ponderosa pine and Douglas-fir dominated forests of the East Zone and Tripod study areas. By supporting a limited number of states and aligning time periods between pathways, the STM offers a simplified representation of the interaction of fire and vegetation with a range of burn severities, including low-severity fire, moderate severity, and high-severity fires as defined by the relationship of predicted flame length to probable tree mortality. In reality, combinations of low and moderate severity fires would result in a continuum of states, reflecting diverse fire effects and forest and fuel structures.

The low elevation moist mixed conifer (MMC) STM shares the same pathways and states as the DMC but with shorter times between states, representing greater productivity and more rapid vegetation development.

Avalanche tracks are a prominent feature of the Kootenay landscape. Vegetation and fuels are variable within avalanche tracks but are generally composed of grasses, sedges, broadleaf deciduous shrubs and coarse downed wood. Three states are supported with a relatively short time interval between states.

Applications

The STMs have potential utility beyond the original scope of this study. By constructing FCCS fuelbeds to represent each state within the pathways, we provide a crosswalk between the states and early and late-successional forest structure and wildlife habitat as well as to above-ground biomass estimates that can be used for evaluating carbon dynamics and potential wildfire emissions. One of the first applications of the STMs for wildlife habitat has been for evaluating mixed severity fire regimes and Canada lynx (*Lynx canadensis*) habitat (Section 4.7). As the incidence and area burned by wildfires is increasing in western North America, carbon fluxes and pollutant emissions from recent wildfires are of increasing concern (Abatzoglou and Williams 2016). Because each state within our STMs is accompanied by an FCCS fuelbed, an estimated total aboveground biomass is available for carbon accounting and can also be used to evaluate potential wildland fire emissions over time using the mixed severity fire modeling tool under different wildfire management scenarios (Section 4.6).

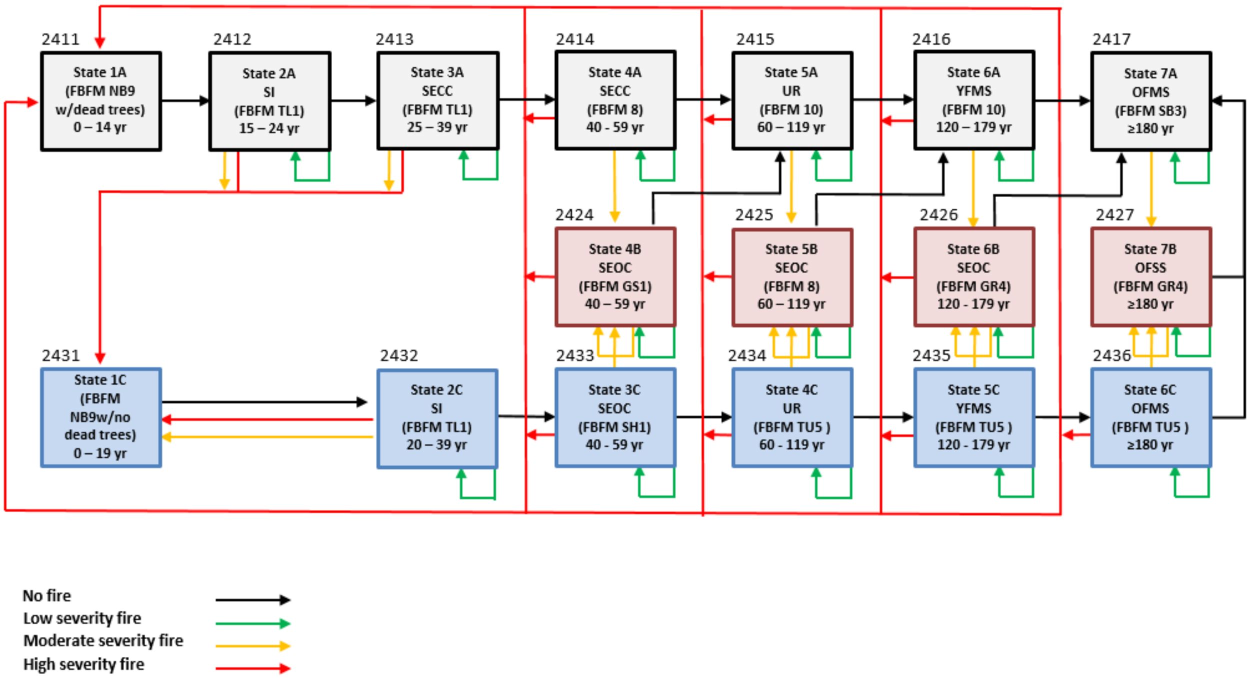

Figure 4.3: Sample cold dry conifer STM for the East Zone study area, representing vegetation and fuel dynamics in Engelmann spruce, subalpine fir and lodgepole pine forests under low, moderate and high-severity fire pathways.

State 1A: Post-fire bare ground. Fuel model NB9. 0-14 yr.

State 2A: Stand initiation. Fuel model TL1. 15-29 yr.

State 3A-4A: Stem exclusion closed-canopy. Fuel model TL1, 8. 30-79 yr.

State 5A: Understory reinitiation. Fuel model 10. 80-129 yr.

State 6A: Young forest multi-story. Fuel model 10. 130-179 yr.

State 7A: Old forest multi-story. Fuel model SB3. ≥ 180 yr.

Figure 4.4: Sample photos of the cold dry conifer fire exclusion pathway (A).

4.5. Povak, N., Salter, R.B., Hessburg, P., Prichard, S.J. and Gray, R.W. In prep. Fire, fuel and vegetation dynamics – modeling wildfire and fuel succession in fire-prone landscapes. Part II: simulation modeling.

In this study, we evaluated the effects of past wildfires on fire growth and severity characteristics and management of subsequent wildfires using a spatial simulation modeling approach. Simulations quantified the influence of wildfire suppression on landscape-level vegetation dynamics and wildfire regime properties. We focused on three study areas that were centered on a recent large wildfire (>40,000 ha) within the northern Cascade and Rocky Mountain regions. For each region, we developed 1) a fire simulation model (FSPro; Finney et al. 2011) to spread individual wildfire events from observed historical (1940 – mid-2000's) ignition locations and daily weather, and 2) custom state-transition models to simulate spatiotemporal dynamics of fuel succession.

Our results showed that while large, cascading fire events occurred at low frequency, fire sizes were moderated by a patchwork of previously burned and non-burnable patches, suggesting a high level of internal system control (Peterson 2002). In addition, structural and compositional conditions of simulated landscapes showed strong correspondence to empirically reconstructed and published HRV estimates for the region (Hessburg et al. 1999, 2000, Table 4.3). This comparison provided unbiased evidence that spatial simulation modeling fairly represented native succession and disturbance processes for each study area.

Time series traces of the structural patterns and characteristics for pathway groups across the 3,000- year simulations revealed system-level behavior. For example, both A and B simulations (**Figure 4.5)** exhibited highly similar behavior, despite being independent realizations of our spatial simulation process. Time series analysis showed that the largest right tailed fire events had the potential to shift the system outside of HRV conditions. However, absent an uncharacteristic abundance of additional large events, HRV conditions resumed within 2-3 centuries. Simulations in cold forests revealed dynamics driven by large events that temporarily shifted systems into non-forest and young forest types, but systems recovered over several decades to more contiguous forest vegetation. Where short intervals between large events occurred, recurrent events profoundly impacted system dynamics, and landscapes were often non-forested for centuries due to reburning. Our results showed that cold forest systems are robust to occasional rare events, but susceptible to change when large event frequency becomes uncharacteristically high.

Compared to cold forests, dry forests showed fewer dramatic changes in forest dynamics driven by frequent fires. Open canopy conditions dominated dry forests, which represented ~30% of the landscape area on average. Open forest conditions were less dominant in moist forests, with ~20% coverage across the landscape. Understory re-initiation (UR) and young forest multi-story (YFMS) classes exhibited greater dominance in moist forests owing to longer fire-free periods in more productive environments. Dry forests were highly robust and evidence of large and damaging fire events over 3000 years was limited. Moist forest were less robust with larger amounts of UR and YFMS conditions, and large fire events could be destabilizing to HRV for 2-3 centuries. Old forest structure did not dominate either dry or moist forests, but could be found in abundance in different watersheds over time.

Table 4.3: Percent composition of structural classes for the Tripod study landscape. Values are summarized across 3,000 years of simulation. Percentages shown here are averaged across all years. Results are for Landscape A, which were very similar to Landscape B. DMC = dry mixed conifer pathway group (PWG); MMC = most mixed conifer PWG; CMC = Cold & Moist conifer forest PWG; CDC = Cold and dry forest PWG. PFSI = preforest + stand initiation structure. PFSI = post-fire/stand initiation, SEOC = stem exclusion open canopy, SECC = stem exclusion closed canopy, UR = understory reinitiation, YFMS = young forest multistory, OFMS = old forest multistory, and OFSS = old forest single story.

PWG	Structure	Median	Minimum	10th percentile	90th percentile	Maximum
DMC	PFSI	21.4	3.5	12.3	30.1	45.3
DMC	SEOC	32.1	14.5	26.6	36.7	46.5
DMC	SECC	5.8	1.3	3.1	10.3	18.8
DMC	UR	16.8	4.8	11.6	22.3	37.8
DMC	YFMS	6.3	0.7	3.2	10.6	18.8
DMC	OFMS	6.6	1.5	3.5	10.5	19.8
DMC	OFSS	10.2	2.7	7.4	13.6	19.8
MMC	PFSI	22.2	3.1	11.5	33.1	43.7
MMC	SEOC	21.1	5.0	15.2	26.6	33.1
MMC	SECC	17.4	6.3	12.4	23.5	35.4
MMC	UR	16.3	4.6	10.2	25.7	41.3
MMC	YFMS	13.3	6.0	9.3	18.4	28.4
MMC	OFMS	4.2	1.5	2.9	6.0	9.9
MMC	OFSS	4.0	2.0	2.9	5.2	7.1
CMC	PFSI	24.6	7.1	13.3	42.1	66.1
CMC	SEOC	13.5	4.8	9.1	19.4	25.8
CMC	SECC	18.8	0.6	6.4	33.2	58.8
CMC	UR	9.7	0.0	1.2	21.2	45.3
CMC	YFMS	13.6	1.0	5.6	25.8	47.8
CMC	OFMS	11.8	4.2	6.7	26.1	38.4
CDC	PFSI	41.5	17.3	30.5	57.4	76.0
CDC	SEOC	7.3	1.2	4.0	12.4	18.5
CDC	SECC	10.9	0.4	2.7	21.8	45.4
CDC	UR	7.1	0.1	1.0	16.0	28.6
CDC	YFMS	12.8	2.5	6.4	22.1	41.0
CDC	OFMS	14.6	5.4	9.9	23.6	36.6

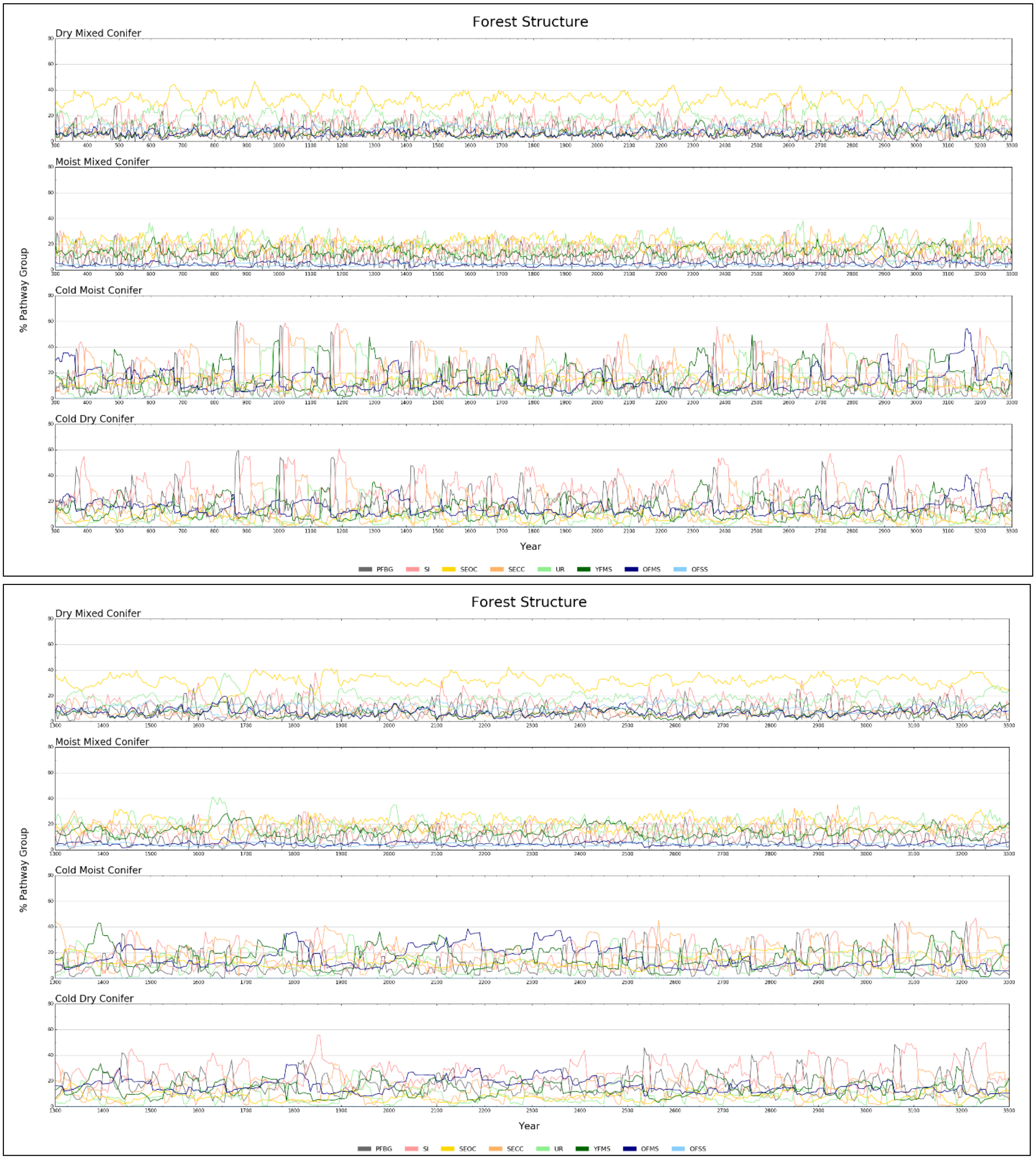

Figure 4.5. The percentage composition of structural classes across two independent 3,000 year simulations. See Table 5 caption for abbreviations.

4.6 Povak, N., Salter, R.B., Hessburg, P.F., Prichard, S.J. and Gray, R.W. In prep. Landscape mosaics under comparative wildfire management strategies in semi-arid forest landscapes of western North America.

Area burned in the western US will double or quadruple in the next 3 years (McKenzie et al. 2004, Westerling et al. 2011). As wildfires burn more area, an increasing amount will occur in previously burned areas (O'Neill et al. 1992, Peterson 2002, Parks et al 2015, McKenzie and Littell 2017). In this study, we compared resulting burn mosaics under four management strategies: 1) Full suppression--complete absence of fire (no ignitions), 2) modern suppression (only escaped fire ignitions ≥97th percentile fire weather are allowed to burn), 3) partial suppression (only managed and escaped wildfires as above are allowed to burn), and 4) no suppression. Our approach allowed us to hold ignition and daily weather patterns constant across management scenarios in order to isolate the role of fire suppression and its influence on burn patterns over time. We then compared the variability of resulting burn patterns to empirical estimates of the HRV of structural conditions to determine the level of departure resulting from each suppression scenario. We illustrate our findings using results from the Tripod fire study area (**Figure 4.6, 4.7**).

For the full suppression scenario, the resulting landscape with fires absent from 1940 to 2005 showed maturation of forests to young and old forest multi-story conditions and from a surface and canopy fuels standpoint, a relatively homogenous landscapes that showed high potential for crownfire initiation and spread. This landscape realization closely resembled the pre-fire Tripod landscape with highly contagious patterns of vegetation and fuels that supported the actual wildfire event (**Figure 4.6**). The modern fire suppression scenario was designed to represent contemporary wildland fire management, wherein 95-98% of ignitions are suppressed, and only ignitions that escape direct suppression (the 2-5%) were allowed to burn. Results showed an infilling of the landscape with intermediate and mature forests, as in the full suppression scenario, and moderate to high potential for crown fire initiation and spread. Neither of these two scenarios resembled the reconstructed HRV conditions for the full range of non-forest or forest structural conditions (**Figure 4.7**).

The partial suppression scenario allowed for managed wildfires in late-summer and fall, and escaped wildfires as defined above. Simulations generally showed fine-to meso-grained landscape mosaics at lower elevations that supported dry forests, and a mix of small to large patches at higher elevations in cold forests. In the no suppression scenario, frequent ignitions sculpted a constantly changing patterns of forest and non-forest conditions. Abundant non-forest conditions provided a constantly shifting patchwork of flashy fuels that frequently spread fire to large areas of the landscape, but severity patterns depended on the time since last fire and the resulting fuelbed of reburned areas. Reburning of surface fuels created the robustness of the landscape in the face of recurrent fires, and forest and physiognomic patchwork complexity resulted not from burning but from incessant reburning. We also found that patches of young and old multistory forest were generally surrounded by recent burns and regenerating forest, not by other complexly structured forest. The full and modern suppression scenarios represented "boom and bust" landscapes, while the partial and no suppression scenarios supported a higher diversity of forest structural conditions and fire behavior. Comparing these alternative landscapes demonstrates that missing any significant proportion of natural ignitions places forests on a course for larger fires and higher fire severity.

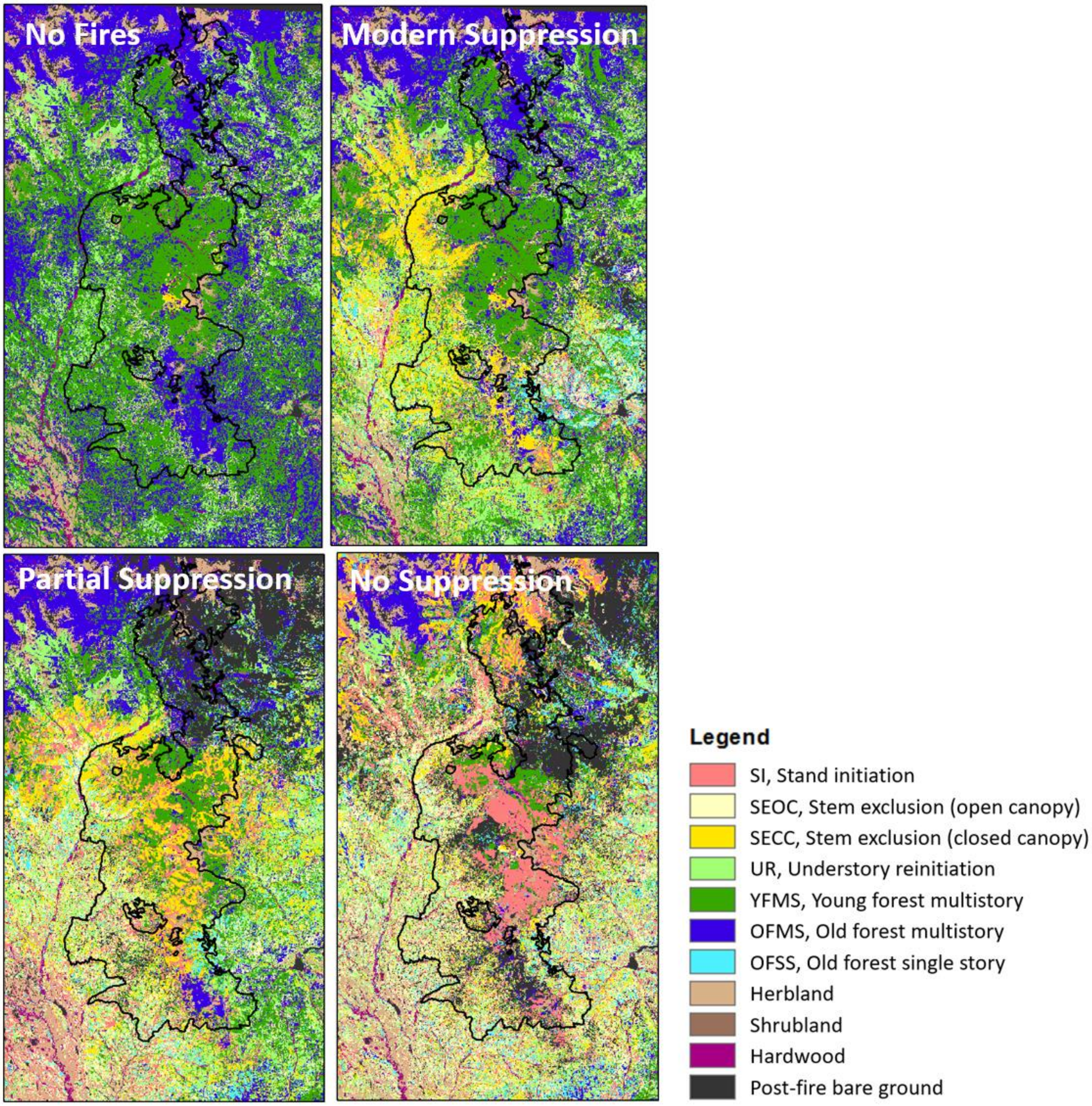

Figure 4.6. Four simulated Tripod landscapes representing Full suppression-No fires, Modern Suppression, Partial Suppression, and No Suppression scenarios. Simulation are from 1940 to 2005, the year before the Tripod fire.

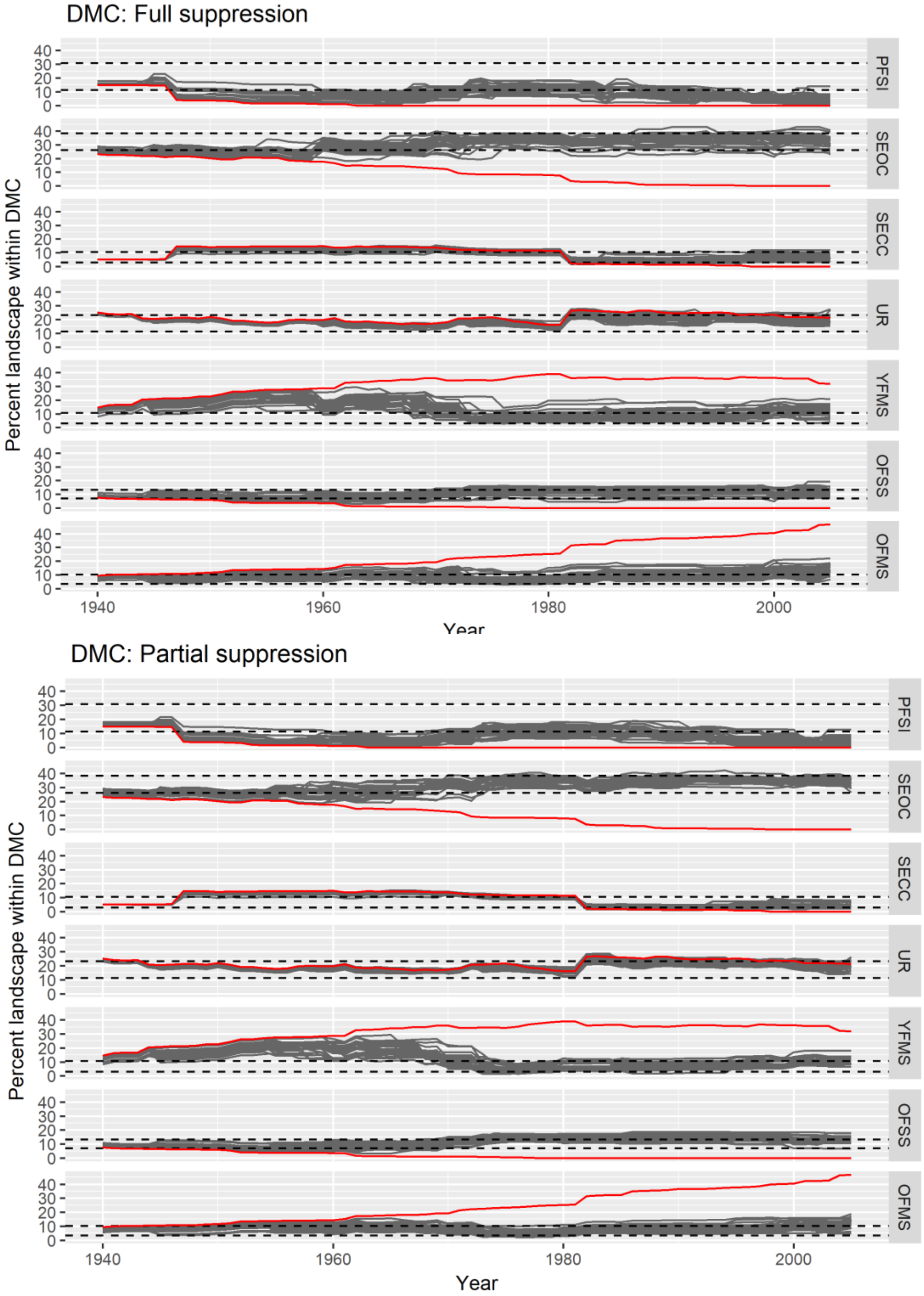

Figure 4.7. Traces of 25 simulations for the full suppression scenario in Dry Mixed Conifer forests. Red lines represent the no-fire scenario as a reference, and dashed lines represent the 10th and 90th percentile bounds of the simulated range of variability, generated from the 3000-yr simulation.

4.7 Gaines, W.L., Hessburg, P.F., Lyons, A.L., Salter, R.B., Prichard, S.J., Vanbianchi, C. and Hodges, K. In prep. Synergistic effects of climate change, large wildfires, and past management challenge the survival of an iconic cat: Canada lynx in the North Cascades, USA. Frontiers in Ecology and Environment.

The combined effects of climate change and large wildfires, fueled by effects of past management practices, challenge current efforts to recover Canada lynx in the North Cascades, USA (Koehler et al. 2008). Canada lynx is a threatened species in the US under the Endangered Species Act, and a focal species that managers use to better understand the native structure and function of sub-boreal forest ecosystems. Canada lynx evolved in an environment shaped by mixed and high severity fire, however, fire regimes in these sub-boreal forests have been dramatically altered.

To understand how these stressors are influencing lynx populations and the sub-boreal ecosystem, we used a spatially explicit carrying capacity model (HexSim), informed by local data on lynx resource selection and life history (Lyons et al. 2016). We used our model to estimate changes in carrying capacity for two time steps: Year-2000, when limited recent wildfires had occurred, and Year-2013 after nearly 138,000 ha of severely burned area had affected nearly half of remaining lynx habitat in our study area. We then spatially linked our carrying capacity model with a new Reburn state-transition model that simulates fire growth driven by actual daily meteorological streams and ignition locations, and then simulated fuel and forest succession in annual time steps after the fires, over a 274,302 ha study area. Simulations were conducted to assess the relative influence of varying both fire management options and their scale of influence on lynx habitat and carrying capacity. Management options varied from no suppression to full suppression, and included allowing for managed wildfires at varying levels (**Figure 4.8**).

Our results demonstrate that recent fires have severely reduced the distribution and quality of remaining lynx habitat, including denning and foraging components. These changes have considerably reduced the long-term capacity of the landscape to support Canada lynx. There has been a nearly 46% reduction in lynx carrying capacity in our study area as a result of the large, high severity fires that have occurred over the past 15 yr. We also discovered that the native fire regime for these forest types, left to its own devices, produced excellent lynx habitat over most centuries in multi-millennial simulations. Our management simulations showed that lynx carrying capacity varies considerably (+/- 20%) by fire management option. Thus, managers will need to carefully consider fire management options when making decisions about lynx conservation.

Assessment of fire management options strongly suggests that active fire management is necessary to restore a diversity of patch sizes, forest structural stages, and habitat conditions that more closely resembles the natural variability of habitat conditions under which lynx evolved. Active management would need to include a large increase in intentionally managed wildfires instead of actively suppressing most wildfires, a much larger footprint of prescribed burning, and in cases where burn only treatments are impossible due to overabundant live fuels, low or free-thinning followed by prescribed burning. The combined influences of past and ongoing fire suppression, increased drought, and longer wildfire seasons, along with recent and projected large fires challenges realistic conservation and recovery of Canada lynx and the boreal forest ecosystems upon which they depend, without active management.

Forest ecosystems that historically had a mixed-severity fire regime are at a critical crossroads in which a legacy of past fire exclusion, human activities and rapid shifts in climate are accelerating rates of change. Due to a notable lack of reference sites, simulation modeling is one of our best options for evaluating the consequences of contemporary fire management and potential alternatives. In this paper, we introduce a series of STMs that represent common forest types within western North America including mixed conifer forests dominated by Douglas-fir and ponderosa pine and cold mixed conifer forests dominated by Engelmann spruce, subalpine fir and lodgepole pine. Although the STMs were originally created within a simulation tool to model mixed severity fire, they also contain forest structural and biomass datasets that are relevant to wildlife habitat suitability, carbon accounting and wildland fire emissions evaluations.

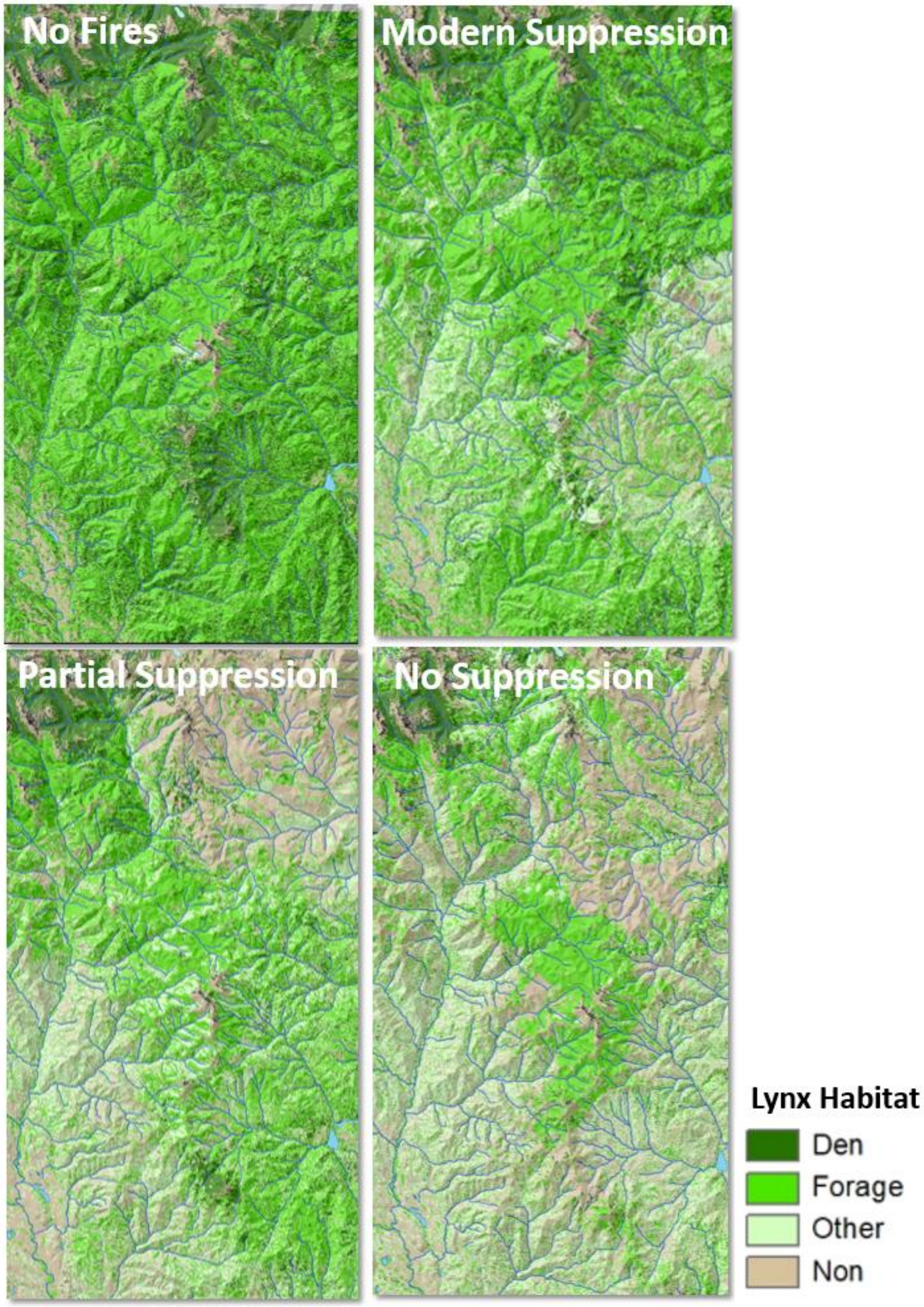

Figure 4.8. Alternative pre-fire Tripod landscapes displayed as suitable lynx habitat.

5. Management Implications

1) *Past wildfires and their role in restoring resilient landscapes*

With increasing western North American area burned, the ecological footprint of past burns and their constituent severity mosaics will influence future wildfire patterns, their severity mosaics, and related forest successional patch and habitat dynamics. Although top-down climatic factors are clear drivers of annual area burned, bottom-up factors, which include topography and land surface form, vegetation type, canopy cover, and related surface fuels, and patterns of past wildfires all were important explanatory variables in each of these large fire events. Past wildfires generally mitigate burn severity--even under extreme fire weather events that are associated with large fires. To better understand how to use prior wildfires (and prescribed burns) in tactical and strategic fire management decisions, it is important to understand how long past fires can remain barriers to subsequent wildfires. This can better understood by evaluating and elucidating thresholds to reburning of variously burned conditions under a range of likely fire weather scenarios. Wildfires, even the large fire events studied here, possess some attributes of self-regulation. Managing for the more likely interactions among sequential events can contribute to restoring the resilience of fire-prone landscapes. Allowing more wildfires to burn under moderate fire weather in dry, moist, and cold forest types has the potential to mitigate future burn severity and promote landscapes that can withstand the impacts of repeated fires, even in the context of climate change.

2) *Implications for wildland fire planning and operations*

Results from our study confirm the use of past fires in wildland fire planning and provide some context for the likely duration of their effectiveness. Quantifying the longevity of past fires as barriers to subsequent wildfire spread under various fire weather conditions will help predict their utility in tactical and strategic fire management decisions. Given the rising cost of fire suppression, knowing when, where and how areas will reburn under varying fire weather scenarios can help to reduce costs of large wildfires while assisting land managers in making fire management decisions that are consistent with land management plans and restoration priorities (Houtman et al. 2013). Since the 2003 Kootenay and 2006 Tripod events, subsequent fires have burned within these landscapes, and they offer insights into how fire operations made use of past wildfires. In the United States, the Wildland Fire Decision Support System includes past fires, including prescribed and wildfires, to provide context for tactical fire management decisions. For example, in the summers of 2014 and 2015, the Tripod Complex area informed resource allocations, and no direct actions were taken where the 2014 Carlton Complex and the 2015 Okanogan Complex fires burned near the border of the Tripod. Similarly, Kootenay National Park is using operational fires, including prescribed crown fires as managed fuel breaks within critical fire corridors to adjacent lands.

3) *Long-term consequences of wildfire management decisions*

The simulation modeling results from our study offer a unique perspective of the long-term consequences of wildfire management decisions – in particular, the implications of fire management decisions for future wildfire events. Results from simulation modeling provide compelling illustrations of how actively removing fires from historically frequent-fire systems have lasting ramifications for landscapes and their relative susceptibility to future fires. Of our four scenarios, the no-fire and modern suppression scenarios represent "boom and bust" landscapes in which continuous mature forests are capable of supporting large fire spread. The partial wildfire and no-suppression landscapes produced finer-grained patch mosaics that would have presented a markedly different landscape to fire managers in the 2006 Tripod Fire. Specifically, the partial and no-suppression landscapes supported a much more diverse landscape that was less susceptible to large, stand-replacing fire events and supported a wide range of forest ages, structural classes and lifeforms. The diversity of the partial and no-suppression landscapes could have provided wildfire managers with options to allow fires to burn into recent fire scars or to position initial attack in safe and defensible positions. Together, these simulated landscape comparisons offer an opportunity to evaluate how past burn mosaics could be used in tactical wildland fire decision making and to investigate longer-term implications of fire management decisions.

4) Influence of past fires on simulated fire size distributions

From our simulation runs, we found that predicted fire spread with FSPro tended to be fairly large on average, and we hypothesized that area burned might be dominated by large fires as a result. However, our results show that large, cascading fire events do occur, but occurred at relatively low frequency, and fire sizes instead are strongly moderated by the patchwork of previously burned and non-burnable patches. This is contrary to the current trends in the western US and Canada where wildfire events appear to be steadily increasing in size. While ongoing climate change is clearly a main driver of these trends through longer, drier and hotter fire seasons, our simulation modeling results suggest the ability of frequent-fire systems to self-regulate over time. Through the development of patch mosaic patterns, self-regulated landscapes provide barriers to fire spread that can influence long-term fire regime properties and possibly mitigate the influences of climate change. These patterns of prior fires provide the system with memory, represented by the spatial patterns of burned and recovering vegetation that variously resist the flow of fire.

5) Implications of wildland fire management decisions on Canada lynx

Our results demonstrate that recent fires have severely reduced the distribution and quality of remaining Canada lynx habitat, including denning and foraging components. These changes have considerably reduced the long-term capacity of the landscape to support lynx. There has been a nearly 46% reduction in lynx carrying capacity in north Central Washington as a result of the large, high severity fires that have occurred since 2003. Simulation modeling of fire and vegetation dynamics over millennia suggests that native fire regimes for these forest types, prior to fire exclusion, likely produced and dynamically sustained an abundance of high-quality lynx habitat over time. Our comparative management simulations showed that lynx carrying capacity varies considerably (+/- 20%) by fire management option. Thus managers will need to integrate wildfire into lynx conservation planning and set goals for their future population trends that incorporate they dynamism of landscape patterns resulting from recurrent wildfires.

6. Research Needed

1) Improved understanding of burn severity in reburn areas.

In Task 1 (Stevens-Rumann et al. 2016), we used burn severity metrics (i.e., RdNBR and dNBR) to evaluate the influence of past burn severity on subsequent burn severity. These indices have been reasonably correlated with changes in vegetation and soil reflectance after fire. However, there are even greater uncertainties associated with evaluating changes in reflectance in previously burned areas. Reburns represent complex surface fuelbed dynamics over time with reduced fuels immediately following fire and then the potential for high surface fuel accumulations depending on vegetation recovery and snag fall contributions to downed wood.

We were able to use a set of validation plots to evaluate burn severity in prescribed burns that were reburned in the 2006 Tripod Complex fire. Producer's accuracy was around 40%, but 95% of the errors were when RdNBR values were close to the cutoff between unchanged and low severity or low and moderate severity (Miller and Thode 2007). Our application of the metrics used continuous values and was not reliant on reburn reflectance being classified into burn severity categories. Kolden et al. (2015) highlight the need to develop ecological thresholds for burn severity mapping using field-validated measures of interest (e.g., tree mortality). We also recommend field studies within different forest types and regions to study the characteristics of surface fuels following fire and rates of forest succession and vegetation over time to build on the recent work summarized by Hudak et al. (2018).

2) Recommended improvements to operational fire spread models in the Wildland Fire Decision Support System

We selected an operational fire spread model for our wildland fire simulations due to the common use of Wildland Fire Decision Support System (WFDSS) for fire management decision making. Our work with FSPro in the Reburn Simulation Tool suggests several areas of improvement for the model and its implementation for WFDSS. Specifically:

- Due to the importance of fuel conditioning on thresholds to burning across elevational gradients and over fire seasons, supporting gridded fuel moisture surfaces in addition to wind grids is essential.
- Fire perimeter growth with and without spotting often gave unrealistically explosive fire growth. We were forced to truncate fires to 14 days and turn spotting off to approximate more realistic fire spread.
- Adjustments to canopy assignments, including canopy base height, were necessary to obtain realistic fire spread.
- Future versions of operational fire models would benefit from the use of realistic fuelbeds and a retirement of surface fire behavior models.
- Due to the coarse grain of our modeling, fine-scale fire dynamics with landform, including cold air drainage pooling and other potential barriers to fire cannot be adequately modeled.

- We were able to use a command-line version of FSPro. Making FSPro publicly available as a command line and open source could contribute to refinements that would address some of these known issues.

3) Improvements to the Reburn simulation modeling tool

We have several refinements to our simulation modeling tool and process envisioned for future projects. These include:

- Refine our state and transition models to decouple surface and canopy fuel assignments. In particular, we need to support separate surface fuel pathways to respond to surface fire severity and time since fire.
- FCCS fuelbeds have been constructed for dry mixed conifer and cold mixed conifer pathway fuelbeds but need to be developed for all states.
- For more comprehensive wildlife habitat assessments, we plan to develop classifications of each state within STMs into early and late seral habitat (e.g., moose, white-headed woodpecker to evaluate tradeoffs)
- We will pursue funding opportunities to conduct field sampling to provide inputs to STMs and associated fuelbeds (carbon, wildlife habitat).
- We envision an eventual linkage with the Tool for Exploratory Landscape Scenario Analysis to support state and transition modeling for Reburn simulation modeling (TELSA; http://wiki.landscapetoolbox.org/doku.php/tools:tool_for_exploratory_landscape_scenario_analysis_telsa).

4) Future projects using the Reburn simulation modeling tool

Our simulation modeling process has led to a number of conversations about future research projects involving managed fire and burn mosaics. In particular, wildland fire and fuels managers are keenly interested in developing similar analytical tools to evaluate the consequences of fire management decisions on landscape resiliency to future climate, fire and insect dynamics. Potential projects include:

- Collaboration with the City of Quesnel, British Columbia about future management options for the Quesnel Timber Supply Area.
- Future research in Kootenay National Park and surrounding areas to evaluate fire and vegetation dynamics and consequences to wildlife habitat under future climatic scenarios.
- Consultation with the Dixie and Fishlake National Forests about development of a similar modeling process to guide wildland fire management decisions in south central Utah.

We have also been in communication with the WFDSS team about incorporation our alternative landscapes as custom landscape files within the WFDSS training module. Recent developments in WFDSS should allow for file imports of custom landscape files, and we will continue working with the WFDSS team to develop a Reburn training module.

7. Project Deliverables

Project deliverables and completion dates are presented in Table 7.1. To date, we have published two manuscripts on the Reburn project and an online review. Two additional scientific manuscripts are in preparation in addition to a guide on the State and Transition Models developed for this study and a draft Fire Management Today article. Deliverables completed under this project but not included in the JFSP proposal include additional work on two literature review papers on the topic of changing fire regimes and the influence of past wildfires on subsequent fires. We also collaborated with Bill Gaines and Andrea Lyons on a follow-up analysis of how fire management strategies, modeled with our Reburn simulation tool, influence critical Canada lynx habitat. A project webinar is planned in November 2018, and we also plan to provide an additional webinar to Parks Canada and fire and fuels managers in Banff, Kootenay and Yoho National Parks.

Table 7.1: Proposed and additional deliverables

Deliverable Type	Descriptions	Delivery Dates
JFSP progress report 1	Progress report to JFSP for FY 2015	Sept 2015
Manuscripts 1-3	Dissertation chapter and two published paper on burn severity analysis of fire-on-fire interactions.	Aug 2016
JFSP progress report 2	Progress report to JFSP for FY 2016	Sept 2016
Conference presentations	6th International Conference on Fire Ecology and Management, San Antonio, TX 7th International Fire Ecology and Management Congress, Orlando, FL	Nov 2015 Nov 2017
Manuscript 4	Tamm Review: Shifting global fire regimes: lessons from reburns and research needs.	Jan 2017
Manager workshop 1	North Central Washington workshop with Okanogan-Wenatchee NF fire staff, Wenatchee, WA	March 2018
Manager workshop 2	Additional workshop presented at the Missoula Fire Continuum Conference, focused on implications of reburn mosaics and wildland fire management strategies on Canada lynx wildlife habitat.	May 2018
Manager workshop 3	Central Idaho workshop in coordination with the JFSP 14-1-02-27 Vegetation Recovery project (A. Hudak) in Moscow, ID.	June 2018
Manager workshop 4	Interior BC workshop in coordination with the City of Quesnel fire management scoping session.	Sept 2018
Training module	This deliverable was changed because WFDSS does not support custom landscape files. All training materials are available on our project website, including sample results and presentations	Sept 2018
Manuscripts 5-9	Scientific manuscripts on simulated landscapes from historic fire start data. We will submit three manuscripts on the Reburn simulation modeling and	In prep

Deliverable Type	Descriptions	Delivery Dates
	STM development and additional manuscript on implications for Canada lynx habitat	
Manuscript 10	We will share our project findings on wildland fire management strategies in Fire Management Today	In prep
JFSP final report	Final report to JFSP	October 2018
Data archive	We will submit project datasets to the Forest Service Research Data Archive and metadata to the Northwest Fire Portal upon publication	Ongoing
Webinars	Two webinars are planned for Northwest Fire Science Consortium and Parks Canada.	Nov 2018 & TBD

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Appendix B: Scientific and technical publications

1. Stevens-Rumann, C. 2015. Legacy of repeated disturbances in mixed-conifer forests. Ph.D. dissertation. University of Idaho, Moscow, ID.

2. Stevens-Rumann, C.S., Prichard, S.J., and Morgan, P. 2014. The effect of previous wildfires on subsequent wildfire behavior and post wildfire recovery. Northern Rockies Fire Science Network Science Review No. 1.

3. Stevens-Rumann, C., Prichard, S., Strand, E., and Morgan, P. 2016. Prior wildfires influence burn severity of subsequent fires. Canadian Journal of Forest Research 46:1375-1385. DOI: 10.1139/cjfr-2016-0185.

4. Prichard, S.J., Stevens-Rumann, C.S. and Hessburg, P.F. 2017. Tamm Review: Shifting global fire regimes: lessons from reburns and research needs. Forest Ecology and Management 396:217-233. https://doi.org/10.1016/j.foreco.2017.03.035

5. Povak, N. Hessburg, P., Salter, B., Prichard, S.J., and Gray, R.W. In prep. Fire, fuel and vegetation dynamics – modeling wildfire and fuel succession in fire-prone landscapes. Part 2: fire simulation modeling. International Journal of Wildland Fire.

6. Prichard, S.J., Gray, R.W., Hessburg, P, Salter, B., and Povak, N. In prep. Fire, fuel and vegetation dynamics – modeling wildfire and fuel succession in fire-prone landscapes. Part I: state and transition models. International Journal of Wildland Fire.

7. Povak, N., Salter, R.B., Prichard, S.J. and Gray, R.W. In prep. Landscape mosaics under comparative wildfire management strategies in semi-arid forest landscapes of western North America.

8. Prichard, S.J., Gray, R.W., Hessburg, P, Salter, B., and Povak, N. 2018. State and transition models of semi-arid forest landscapes in western North America: fire and fuel pathways. Draft available online at: https://depts.washington.edu/nwfire/reburn.

9. Gaines, W.L., Hessburg, P.F., Lyons, A.L., Salter, R.B., Prichard, S.J., Vanbianchi, C. and Hodges, K. In prep. Synergistic effects of climate change, large wildfires, and past management challenge the survival of an iconic cat: Canada lynx in the North Cascades, USA. Frontiers in Ecology and Environment.

10. Prichard, S.J., et al. In prep. Wildfires as fuel treatments – burn mosaics and wildfire management. Fire Management Today. Draft available online at: https://depts.washington.edu/nwfire/reburn.

Oral presentations and abstracts:

Stevens-Rumann CS, Prichard S, Morgan P. 2015. The evaluation of burn mosaics on subsequent wildfire burn severity and postfire effects. AFE Fire Congress, November 2015, San Antonio, TX.

Prichard, S.J. Fire on our Side Special Session, November 19, 2015. Past burn mosaics in the North Cascades Mountains: implications for wildland fire management. 6th International Conference on Fire Ecology and Management, San Antonio, TX.

Prichard, S.J. and Stevens-Rumann, C. Special Session, November 16, 2015. Wildland fire-on-fire interactions: A review of fire-prone ecosystems and implications under a changing climate. 6th International Conference on Fire Ecology and Management, San Antonio, TX.

Stevens-Rumann CS, Prichard S, Morgan P, Higuera P, Harvey B. 2016. Wildfires for better or worse? Natural Areas Association Conference, October 2016, Davis, CA.

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Prichard, S.J., Gray, B., Hessburg, P., Povak, N. and Salter, B. November 29, 2017. Influence of Past Burn Mosaics to Future Fire Behavior and Implications for Management. Orlando, FL.

Prichard, S., Hessburg, P. and Gaines, W. May 21, 2018. Linking wildfire burn mosaic and lynx habitat modeling. Missoula Fire Continuum Conference. Missoula, MT.

Appendix C: Project metadata

Metadata have been completed for Task 1 and Task 2 datasets using the FGDC Content Standard for Digital Geospatial Metadata (FGDC-STD-001-1998). Final datasets will be archived with the Forest Service Research Data Archive as they are published and will be made available on the Northwest Fire Portal (http://www.frames.gov/northwest). Links to archived data and published articles will also be available on the FERA webpage (http://www.fs.fed.us/pnw/fera).

Task 1 Datasets:

- Input geospatial data tables for the SAR analysis by study area

Task 2 Datasets

- Historical weather files
- Wind grids
- Base landscapes