FINAL REPORT

Landscape fuel treatments and wildland fire management strategies within recent large fire events

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List of Abbreviations or Acronyms

BB, Broadcast burn

CC, Clearcut

CIR, Colville Indian Reservation

CNF, Colville National Forest

FL, fireline

FMO, Fire management officer

GEE, Google Earth Engine

MTBS, Monitoring Trends in Burn Severity

NIR, near infrared

NDVI, Normalized Difference Vegetation Index

OWNF, Okanogan-Wenatchee National Forest

PB, Pile burn

PCNM, principal components of neighborhood matrices

RAWS, Remote Area Weather Station

RBR, Relativized Burn Ratio

RD, ranger district

RdNBR, Relative Differenced Normalized Burn Ratio

RF, Random Forests

SAR, Simultaneous Autoregression

SBS, Soil Burn Severity, Burned Area Emergency Response database

SWIR, short wave infrared

UB, Underburn

WADNR, Washington State Department of Natural Resources

WDFW, Washington Department of Fish and Wildlife

Abstract

As land managers strive to implement the National Cohesive Wildland Fire Management Strategy, guidance is critically needed on where and how landscape fuel reduction treatments can mitigate future fire impacts and assist in active fire management. In this project, we evaluated the effects of past fuel reduction treatments, including prior wildfires, on fire severity and firefighting operations within recent large fires of north-central Washington State. Past treatments spanned multiple agencies and land ownerships, including private holdings, Colville Indian Reservation (CIR), Colville (CNF) and Okanogan-Wenatchee National Forests (OWNFs), Washington Department of Fish and Wildlife (WDFW) and Washington Department of Natural Resources (WA DNR) lands. We compiled geospatial layers of past wildfires and fuel treatments and evaluated how treatments contributed to two central goals of the Cohesive Strategy -- restoring fire resilient landscapes and promoting safe and effective firefighting response. Through landscape modeling of fire weather, biophysical variables and past fuel treatments, we assessed how fuel treatments in the context of other drivers of fire severity performed in recent large wildfires events.

Fuel reduction treatments occupied a small portion of the total study area but were still significant factors in mitigating fire severity. Compared with first-entry fires, reburned areas exhibited a greater influence from bottom-up factors (e.g., topography, fuels, and past wildfire burn patterns) compared to top-down drivers (i.e., climate, fire weather). Maximum wind speed and direction were strongly correlated with higher burn severity, particularly for first-entry fires. Study fires burned across large environmental gradients, and models revealed a general trend of higher severities in cooler and less arid climatic settings with higher fuel moistures, typical of higher elevation mixed conifer forests. Given that weather and vegetation conditions can vary widely across a given fire -- particularly those that burn for multiple weeks and months -- we also assessed drivers of severity within the 10 largest progression intervals separately to better understand what drove severity under the most extreme conditions. The relative importance and direction of drivers varied more across burn days than across fires. Furthermore, bottom-up drivers were still influential within these burn periods suggesting that large spread days are not driven by top-down factors alone. These findings underscore how each fire spread event has a unique set of factors that drive fire behavior and severity. As such, building predictive models of fire severity for future fires will be difficult given the complexity and non-stationarity of the relationships within and among top-down and bottom-up factors.

To evaluate how treatments assisted firefighting operations, we interviewed local area fire and fuels managers to compile lessons learned about specific ways treatment type, configuration, and landscape position assisted in safe and effective wildfire response. One of the key findings was that forest thinning and especially past burning provided opportunities for low-intensity burnouts that effectively corralled summer wildfires but also, where crews practiced patience and used burning techniques to mitigate fire behavior and severity, served as maintenance burns within treated areas. We also evaluated a new method for measuring fireline effectiveness. Overall, a total of 2205 km of fireline was evaluated in this analysis; not counting roads as completed line, a total of 1742 km of dozer and hand lines were constructed. Because wildfires had such large perimeters, the amount of fireline did not exceed the total fire perimeter for most wildfires. Fireline engagement varied considerably with very low engagement where fires were mainly in roadless areas, and firelines were constructed as contingency lines. Not surprisingly, firelines were more effective in low severity burned areas vs. high severity areas. Finally, using operational fire models within the Interagency Fuel Treatment Decision Support System, we evaluated how a range of fuel treatment intensities influenced burn probability and predicted flame length surfaces. Treatment scenarios that had over 40% of the area treated resulted in substantial reductions to both burn probability and conditional flame length, suggesting that if scaled to 30 to 40% of the landscape, fuel reduction treatments can effectively reduce fire potential and if fires still occur, reduce the intensity and potential severity of summer wildfires. Because fire heeds no administrative boundaries, our emphasis on multiple land ownerships is particularly relevant in evaluating how future fuel reduction treatments can be coordinated across ownerships and land allocations.

Keywords

Adaptive management, climate change, Cohesive Strategy, fireline effectiveness, firefighting, fire severity, fuel treatments, landscape ecology, mixed conifer forests, wildfires, wildland fire management

Acknowledgements

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Objectives

This project directly responded to the JFSP 2017 Task 1: Landscape fuel treatment strategies and wildfire management by evaluating treatment effectiveness and firefighting response during the record-setting wildfire seasons of 2014 and 2015 in north-central Washington. Our central objective was to provide critical information about fuel reduction treatment effectiveness and cross-boundary strategies to stakeholder groups that are working to implement the Cohesive Strategy and restore landscape resiliency to fire. Specific task-based objectives included:

Task 1: Evaluate the effectiveness of fuel reduction treatments in reducing burn severity in the context of topography (e.g., slope position, site climate) and fire weather (e.g., wind, temperature, humidity).

Task 2: Interview incident command teams who were on assignment during the 2014 and 2015 wildfires, document how specific fuel reduction treatments assisted safe and effective fire response, and report lessons learned for future treatment planning (Task 2a). With an opportunity to work with a postdoctoral researcher at Oregon State University, we modified this task to include an evaluation of fire line effectiveness metrics (Task 2b).

Task 3: Through simulation studies, evaluate the type, extent, and landscape configuration of treatments required to restore landscape resilience to wildfires and influence wildfire management strategies, including priorities for suppression and managing wildfires for resource benefit. With the new Interagency Fuel Treatment Decision Support System, we were able to modify this task to create simulations within the system that can be modified by local managers to further evaluate actual fuel treatment strategies that can guide future implementation of the Cohesive Strategy using priority landscapes identified within the 20-year Forest Health Strategic Plan for Eastern Washington (https://www.dnr.wa.gov/publications/rp_forest_health_20_year_strategic_plan.pdf).

Background

Under rapid climate change and increasingly severe wildfire seasons (Parks and Abatzoglou 2020), the National Cohesive Wildland Fire Management Strategy (Cohesive Strategy) calls for an all hands-all lands approach to increasing the pace and scale of fire and fuels management. The Cohesive Strategy has three interrelated goals including fostering resilient landscapes, fire adapted communities, and safe and effective wildfire response. The 2017 JFSP Funding Opportunity Notice included tasks aimed at informing science-based implementation of the Cohesive Strategy. Three research needs were identified, including 1) identify the characteristics of landscape fuel treatment strategies that allow for effective and safe use by firefighters to manage wildfires for resource management objectives and asset protection, 2) evaluate how the effectiveness of landscape fuel strategies is constrained by different social, ecological and other factors, and 3) develop metrics that are scientifically defensible and measurable for evaluating the effectiveness of landscape fuel treatment strategies in terms of allowing for safe and effective use by firefighters.

Materials and Methods

Study Area

We studied large wildfires that burned in north-central Washington State in 2014 and 2015 (**Figure 1**). Regional climate is strongly seasonal with cold winters in which most of the precipitation falls as snow, and warm, dry summers. Vegetation ranges from low-elevation shrub steppe and dry mixed conifer forests dominated by ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) to montane forests dominated by lodgepole pine (*P. contorta*), Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*). Moist riparian areas support mixed assemblages of aspen (*Populus tremuloides*), black cottonwood (*P. trichocarpa*) and mixed conifers. Topography is highly dissected with steep elevational gradients and strong aspect differences in vegetation between more open dry forests on southerly aspects and denser forests on northerly aspects.

The 2014 and 2015 wildfire seasons were influenced by a multi-year regional drought. The 2014 summer wildfire season was preceded by a warm, wet autumn period followed by low winter snowfall and early snowmelt. An early summer heat wave was followed by a mid-July lightning storm which ignited several small fires in the Methow Valley, Washington. A major wind event with sustained winds over 48 km/hr caused these fires to erupt into a record-breaking wildfire event that burned over 64,000 ha in a single fire spread event on July 17th. Over the next several days, the 2014 Carlton Complex fires grew to 102,000 ha. A major rainfall event (> 5 cm) followed on July 23rd dampening fire behavior and contributing to rapid containment.

With continuing drought conditions, the 2015 wildfire season strongly resembled the 2014 wildfire season. An exceptionally wet autumn season was followed by a winter with low snowfall and early spring snowmelt. By early July, live and dead fuels of low elevation forests and shrub steppe were receptive to burning. A series of wildfires ignited by lightning and people spread under hot, dry and often windy conditions. **Table 1** provides more details on the 17 major fire events we evaluated in this study.

Task 1: Burn severity analysis (Povak, Griffey and Prichard)

We first started our burn severity analysis using the 2014 Carlton Complex dataset (**Figure 2**). The main objective of this study was to evaluate the effectiveness of previous fuel treatments and other drivers of forest fire severity in an exceptionally large and severe wildfire event. In past studies (Prichard and Kennedy 2014, Povak et al. 2020), our team had used two complementary methods of geospatial fire severity modeling, including Simultaneous Autoregression (SAR) and Random Forest (RF) modeling. For the Carlton analysis, we conducted a side-by-side comparison of the models and their supported inferences. The SAR modeling approach is well documented in a geospatial analysis of fire severity in the 2006 Tripod Fire (see Prichard and Kennedy 2014, Kennedy & Prichard 2017). Povak et al. (2020) detail

RF methods used to evaluate overall drivers of fire severity in the 2013 Rim Fire in addition to a spatial analysis of local variable importance.

Because the SAR and RF modeling approaches were complementary and supported nearly identical model inferences in our Carlton study (Prichard et al. 2020), we focused on RF modeling for a second fire severity analysis of our entire study area, including major 2014 and 2015 wildfires listed in **Table 1**. The RF modeling approach offers the advantage of evaluating global predictors of fire severity as well as an evaluation of local predictor importance at a given location. Relying on global interpretations of predictor variable influences across all the data may obfuscate variability in drivers of fire severity of space and time. To date, our team had focused on modeling drivers of fire severity for single wildfire events. However, each large wildfire event is better described as a compilation of many distinctly different burn periods with unique combinations of fuel conditions, landform, and fire weather. Reconstruction of fire progression intervals in the 2014 and 2015 wildfires allowed us to not only evaluate drivers of fire severity within each wildfire but also to evaluate how drivers of fire severity ranged from extreme, wind-driven fire spread periods to milder weather days.

One of the most challenging aspects of a fire severity analysis that involves evaluating the performance of past fuel treatments is to ensure that the treatment records are spatially accurate with correct attributes, including treatment type and date. For example, we obtained records from the US Forest Service Activity Tracking System (FACTS database) for past harvests and prescribed burns from 1995 to present. However, careful review of treatment polygons with pre-wildfire orthoimagery (NAIP images from pre-2014) was required to re-digitize many treatment polygons to correct for digitization and projection errors. Similarly, we contacted the Methow Valley and Tonasket Ranger Districts to validate the FACTS-based treatment layer with local harvest and burning records. We obtained similar records from the Washington State Department of Natural Resources, Washington Department of Fish and Wildlife, and the Colville Indian Reservation. All records were quality assured against pre-burn NAIP imagery before compiling them into a master geodatabase.

Past wildfires are considered another type of fuel reduction treatment. We were able to use an existing severity atlas developed from the complementary JFSP-funded NEWFIRE project (Cansler et al. *in press*). The NEWFIRE project was aimed at understanding the role past wildfires can play in achieving restoration goals and incorporated this information into a post-fire landscape-level treatment strategy. The NEWFIRE group added to the wildfire atlas developed by Cansler and McKenzie (2014), which includes fire severity patterns for small fires >10ha and <400 ha (MTBS minimum size threshold) from 1984 - 2008 to include smaller fires through 2017.

Simultaneous Autoregression Modeling

For the Carlton analysis, we used the SAR modeling approach to develop predictive models of fire severity based on past fuel treatments, past wildfires, landform variables, day-of-burn weather variables, vegetation type and canopy fuels. SAR modeling incorporates spatial autocorrelation into the predictive model by integrating data on the local neighborhood of severity surrounding a given cell. In a previous study, Kennedy and Prichard (2017) evaluated the influence of neighborhood on SAR model inferences and found that using the full neighborhood (i.e., no subsampling of pixels) resulted in the strongest model inferences. For the Carlton Complex dataset, we developed SAR models using the spautolm function in the spdep package v1.0.2 in R (Bivand and Piras 2015) to predict fire severity indices by fuel treatment, topography, vegetation and fuels, and weather variables across the North and South study areas, including untreated pixels. These models include a linear combination of predictor variables as well as spatially autocorrelated errors terms.

Random Forest Modeling

Random Forest modeling (Breiman 2001, Ishwaran and Kogalur 2018) is an ensemble regression tree modeling system in which hundreds to thousands of regression trees (De'ath and Fabricus 2000) are developed with iterative subsets of the data and predictions of fire severity are averaged across trees. Our application of RF models for fire severity analysis is detailed in our published paper on the Carlton analysis (Prichard et al. 2020). A brief overview of our approach is provided here. Fire severity was represented as the relativized burn ratio (RBR, Parks et al. 2014a) using the methodology of Parks et al. (2018b), which takes the average of all valid pixels (e.g., cloud-free) over a range of pre- and post-fire dates to calculate RBR, rather than relying on individual scenes to represent both pre- and post-fire conditions. To compare RF with SAR modeling approaches in the Carlton Complex, we developed RF models for the two separate study areas (North and South). Within each study area, pixels were selected from a 270-m grid to reduce local autocorrelation among samples. For the analysis of all fires from 2014 and 2015 wildfire seasons, we again used 270-m spacing between sample points and created both a global model across all wildfires as well as separate RF models for each wildfire.

Although our grid spacing eliminated local spatial autocorrelation among sample points, the variability of fire severity at scales larger than the 270-m neighborhood still exist and can be explained through the inclusion of spatial autocorrelation variables within RF models. Following Povak et al. (2020), we used principal components of neighborhood matrices (PCNM), a special case of spatial eigenvector maps, which incorporates spatial predictor variables into the RF analysis (Prichard et al. 2020). Once final models were developed, variance decomposition (Borcard et al. 1992) was used to quantify both the unique and shared variance explained by several predictor variable groups representing top-down controls (i.e., climate, fire weather), bottom-up controls (i.e., topography, fuels, and past management), and spatial autocorrelation (represented by PNCM axes). Residual variance was defined as the remaining variance not explained by the models.

The full set of predictor variables evaluated for final severity models is provided in **Table 2**. Variable reduction was conducted for each model to balance model complexity with model performance. Among correlated variables, those with the highest correlation with RBR were retained. The remaining variables were sequentially reduced using backwards elimination. Final models were run using the ranger v0.12.1 package (Wright and Ziegler 2018).

Models were first developed for the Carlton Complex (North and South region) and then expanded in a subsequent analysis to include individual large fire events that burned in eastern Washington between 2014-2015. Several refinements were made to expand our RF modeling system to the larger study area. These included the use of gridded weather data rather than relying on a single RAWS station for daily weather, the use of updated fire severity metrics using Google Earth Engine (Parks et al. 2018b), refined treatment data, and use of Shapley values to evaluate the influence of local variable importance (Komisarczyk et al. 2021). Local importance was assessed using Shapley values, which derives a value for each predictor variable for each raster cell that describes how much each predictor contributes to the deviation, in terms of magnitude and direction, from the average RBR across all raster cells. In practical terms, these values tell you how influential a given predictor variable was at determining RBR at a given location and if it contributed to increased or decreased RBR.

Table 1: Summary statistics of major wildfires in north-central Washington in 2014 and 2015 including total burned area including non-forested area, percentage of forested area, and percentage of forests that burned at high (H), moderate (M), low (L) and unburned/very low (U) severity.

Wildfire Name	Total area (ha)	Forested area	Forest fire severity
		2014 Wildfires	
Carlton Complex	96,468	33%	H 44%, M 34% L 18%, U 3%
Devil's Elbow Complex	7,796	72%	H 12%, M 43%, L 38%, U 7%
		2015 Wildfires	
21 Mile Grade	654	59%	H 13%, M 70%, L 17% U 0%
Chelan Complex	36,114	35%	H 26%, M 36%, L 26%, U 11%
First Creek	2,024	53%	H 49%, M 34%, L 16%, U 1%
Graves Mountain	2,823	93%	H 10%, M 30%, L 47%, U 14%
Lime Belt	48,663	48%	H 10%, M 41%, L 41%, U 8%
Little Bridge Creek	1,193	87%	H 44%, M 37%, L 16%, U 3%
Lone Mountain 1	607	84%	H 31%, M 45%, L 19%, U 5%
Newby Lake	764	84%	H 62%, M 26%, L 9%, U 3%
North Star	83,834	83%	H 10%, M 36%, L 47%, U 7%
Renner	4,756	89%	H 4%, M 37%, L 53%, U 6%
Stickpin	18,740	96%	H 45%, M 32%, L 19%, U 5%
Tunk Block	61,501	31%	H 21%, M 42%, L 30%, U 6%
Twisp River	3,837	34%	H 27%, M 38%, L 35%, U 1%
Upper Falls	2,448	91%	H 64%, M 27%, L 9%, U 1%
Wolverine	21,253	84%	H 46%, M 38%, L 12%, U 3%

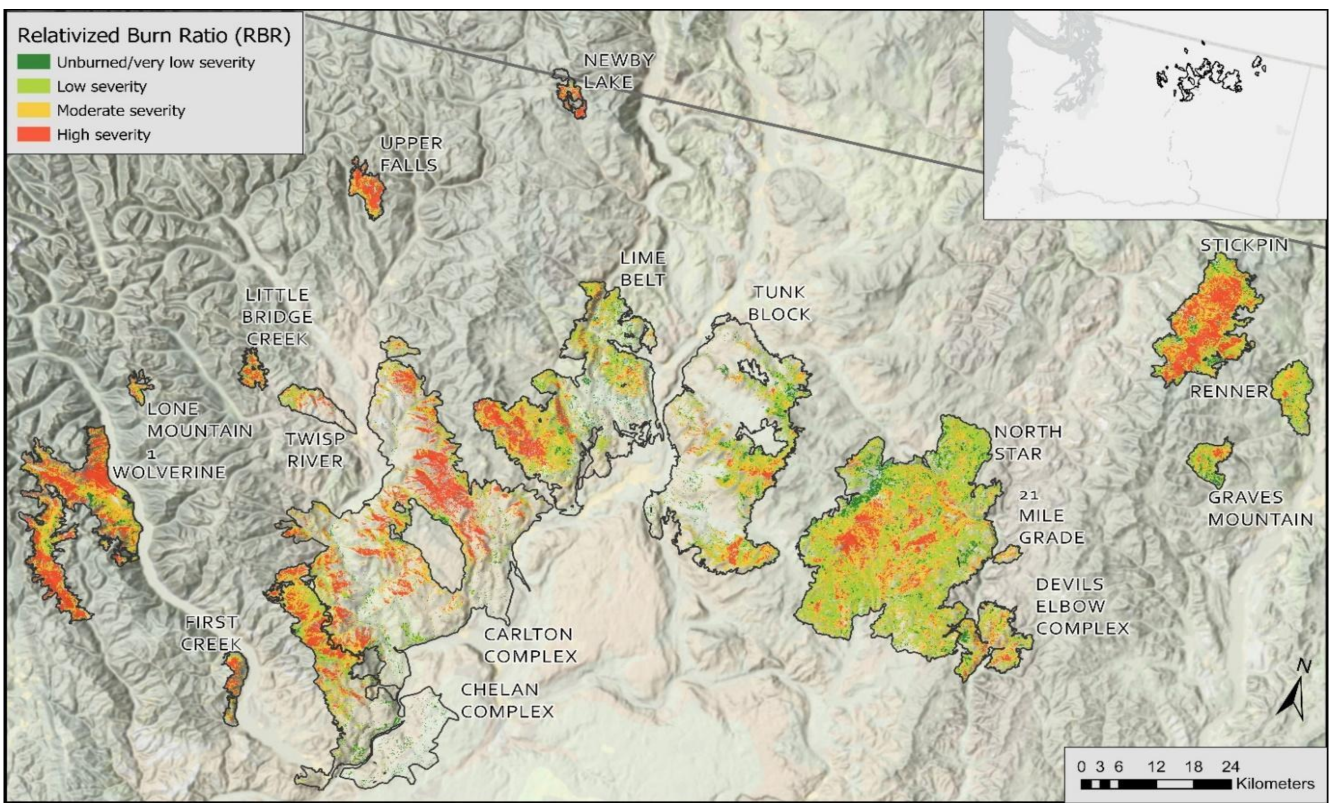

Figure 1. Study area fires with a gradient of low relativized burn ratio (RBR, green) to high (red) values.

Table 2: Final variables used in the RF models of all 2014/2015 wildfires. A listing of predictor variables used in the Carlton analysis is included in Prichard et al. (2020).

Dataset	Description
Treatment	
- Distance to Past Fire (DistFire_20y)	Distance from past fire edge, meters, including wildfires within past 20 years
- TSWildfire	Time since last wildfire, years
- Treat	Clearcut (CC), clearcut and broadcast burn (CC_BB), shelterwood and underburn (SW_UB), thin-only harvest (Thin), Thin and mastication or thin and piled (ThinPileMast), thin and prescribed under burn (ThinUB), thin and pile burn (ThinPB), landscape burn (UB), no treatment (none)
- RxBurn	Presence/absence of historical prescribed burn
- MaxRdNBR	Past RdNBR
- TSRx	Time since last prescribed burn
- TSHarvest	Time since last harvest
- TSTreat	Time since last treatment including harvests and prescribed burns
Topographic variables	
- Slope	Slope gradient, %
- TPI_Ridge_1200	Ridge-like classification of TPI at 1200-m neighborhood.
- TPI_Valley_1200	Valley-like classification of TPI at 1200-m neighborhood.
Vegetation and fuels	
- CBH	Canopy base height, m (LANDFIRE 2012)
- FuelMoisture100hr	100-hour dead wood
- Cover Type	Reclassification based on Existing Vegetation Type (LANDFIRE 2012) including: dry mixed conifer, riparian forest or woodland, moist mixed conifer, Douglas-fir, subalpine forest, lodgepole pine, Engelmann spruce- subalpine forest, ponderosa pine
- Normalized Difference Moisture Index (NDMI)	Calculated as (NIR – SWIR)/(NIR + SWIR) used as an index of live fuel moisture. Composites of one year pre-fire imagery from GEE –Parks et al. (2018b)
- Normalized Difference Vegetation Index (NDVI) of non-forest (NDVI_NF_750)	Mean NDVI of all non-forested cells within 750 m moving window around forested cells. Composites of one year pre-fire imagery from GEE –Parks et al. (2018b)
Weather variables (summarized by progression interval)	
-	
- Maximum Daily Temperature	Maximum daily temperature, °C GRIDMET from Abatzoglou et al. (2013)
- Maximum Relative Humidity	Maximum relative humidity, % GRIDMET from Abatzoglou et al. (2013)
- Maximum Gust Speed	Maximum wind gust, m sec^{-1} Nearest RAWS station was used to summarize hourly data over the progression interval.
- Maximum Gust Direction	Wind direction of maximum gust speed, transformed to linear variable between 0-2 following Beers et al. (1966). Nearest RAWS station was used to summarize hourly data over the progression interval.

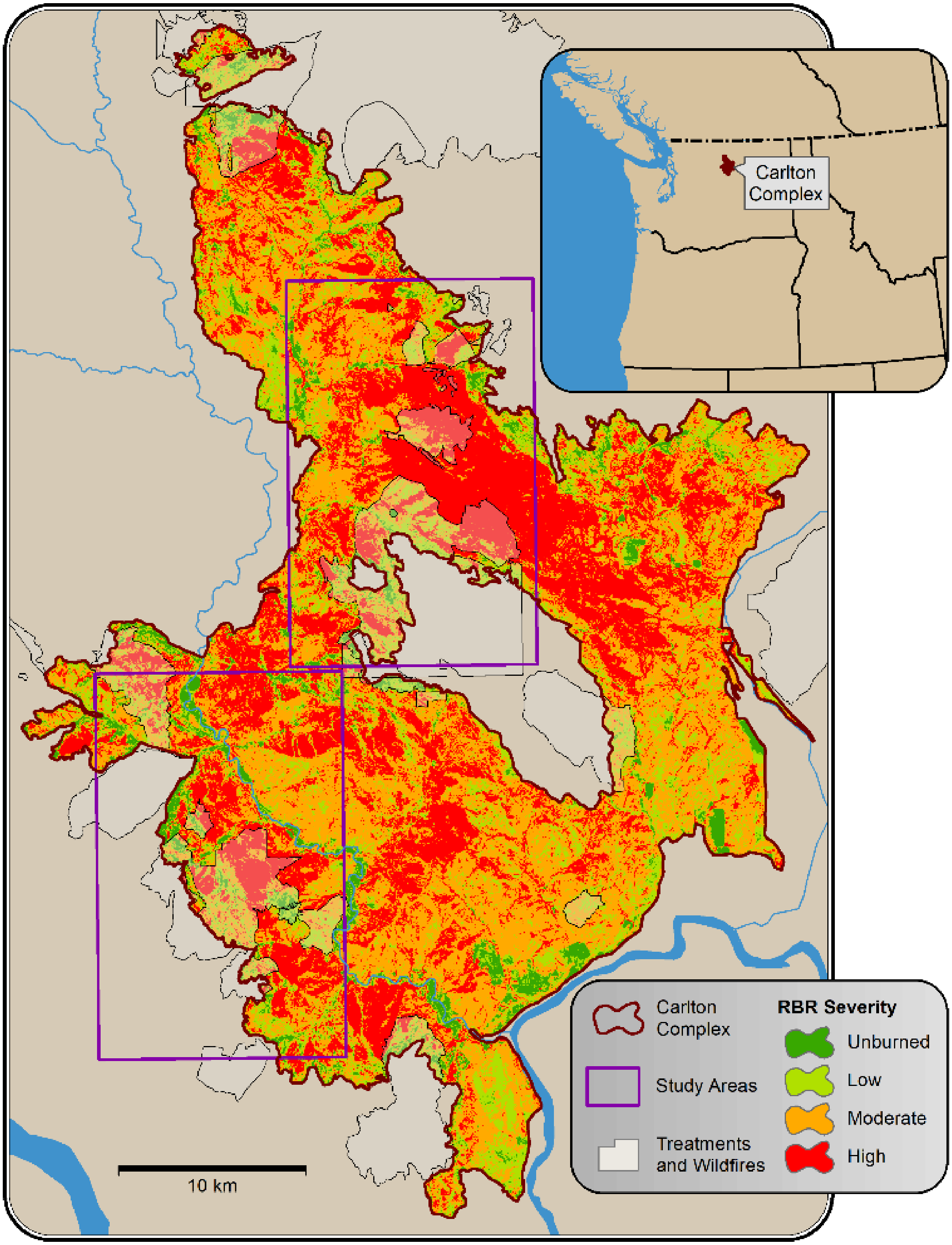

Figure 2: Carlton Complex final burn perimeter with a burned area reflectance classification based on RBR. North and South study areas are outlined in purple.

Task 2a: Evaluation of effective firefighting response (Prichard, Gray)

The original plan for Task 2 of this project was to interview Incident Management Teams (IMT) and document lessons learned about past fuel treatment effectiveness. This effort was to be coordinated with Janean Creighton at Oregon State University. However, we quickly learned that incident management records were incomplete both in the physical fire boxes that were stored at the Okanogan-Wenatchee and Colville NF supervisors offices and within the Inciweb records. Daily incident management plans are typically archived in fire boxes and on Inciweb, but many of the file folders associated with these planning documents were empty. We also obtained access to the Wildland Fire Decision Support System to learn what records were stored within that system and discovered that daily planning records were too inconsistent to be reliable to support structured interviews with past IMT staff.

During the first year of our project, we held in person meetings and site visits with local fire managers, including Lonnie Cawston and Rebecca Peone with the Confederated Tribes of the Colville, Matt Castle from the Okanogan-Wenatchee Supervisors Office, Monique Wynecoop from Colville NF, Tod Camm and Shawn Plank, Fire Management Officer (FMO) and Assistant FMO for the Tonasket Ranger District, Matt Eberline from the WA DFW, and Steve Harris from WA DNR's Colville Office to discuss the 2014 and 2015 wildfire events and specific examples of where fuel treatments assisted with a safe and effective wildfire response (**Figure 3**). Lessons learned are reported in the Results and Discussion section of this final report and are also highlighted on our project website.

Figure 3: Field visit with Tod Camm (Tonasket RD) and Lonnie Cawston (Colville Tribes), discussing a successful fuel reduction treatment within the Lost Creek Project that was used to conduct careful burnout operations in advance of the 2015 North Star Fire.

Task 2b: Fireline Effectiveness Study (Lemons, Kerns and Prichard)

Due to the paucity of firefighting records and relatively low instances where networks of fuel treatments were used in firefighting, we did not end up working with Janean Creighton to conduct interviews with Incident Management Teams. Because of this, we had both time and budget to modify this task to include a new project. Through Janean's connections with Becky Kerns, we were able to shift the funding to support Rebecca Lemons, a postdoctoral researcher at Oregon State University, to conduct a study on fireline effectiveness.

As the incidence, size and severity of western wildfires increase, firefighting continues to grow more complex and costly. Large wildfires are associated with high firefighting costs for direct suppression and for post-fire rehabilitation work (Calkin et al. 2015). The 2014 and 2015 wildfires of north-central Washington were associated with a large network of firelines, and our goal for this study was to both document the type and extent of firelines used in these large wildfire events and where and when they were effective. Several smaller wildfires were considered in this analysis that were not included in our fire severity analysis (Task 1).

A recent paper by Gannon et al. (2020) provides a geospatial technique to evaluate fireline effectiveness on large wildfire events. We initiated this work by holding a planning meeting with Ben Gannon and Matt Thompson to discuss an approach to evaluate their technique on the 2014/2015 wildfires as part of Task 2. Specifically, Gannon et al. (2020) introduced four effectiveness metrics to evaluate fireline effectiveness. These include:

- **Tr**: Ratio of total fireline length versus the total wildfire perimeter. This metric provides a measure of fireline investment for a given wildfire event.
- **Er**: Ratio of engaged fireline versus total fireline length. This metric evaluates how much fireline was engaged in the wildfire (either held or burned over) and can be used to assess if fireline was used or warranted.
- **HEr**: Ratio of held fireline versus the total fireline that was engaged by the fire. This metric provides an assessment of the actual effectiveness of constructed fireline in containing wildfires.
- **HTr**: Ratio of held fireline to total fireline length. This metric provides an overall assessment of how well firelines performed, incorporating both where firelines contained fire spread and the investment in fireline construction.

We applied the Gannon method to fireline records for 13 large wildfire events in our study area (**Table 6**, listed in Results/Discussion section). Because this is a relatively new method, we had two main objectives for this analysis, including 1) to evaluate the overall fireline suppression effort in our study area wildfires and how well major types of firelines (dozer lines, hand lines and roads as completed lines) performed and 2) a sensitivity analysis of how fireline metrics and interpretations are influenced by differences in source data (specifically corrected vs uncorrected fireline datasets and source perimeter datasets), buffer size, and fire severity.

We evaluated three types of fireline (completed dozer line, hand line, and road as completed fireline) for this analysis as they were the most common, easiest to interpret for needed corrections, and currently implemented across the United States for firefighting. Geospatial layers of firelines based on final perimeter records stored for each of our study area fires were obtained from online Inciweb folders or firebox records at the supervisor's offices at Colville and Okanogan-Wenatchee NF. Specifically, final perimeter layers contained constructed and existing roads that were used as firelines and were being evaluated for rehabilitation work. Preliminary review suggested that many records contained some digitizing and classification errors that could be improved through redigitizing lines and correcting attribute tables. One person was used for all fireline corrections, to minimize judgement errors or bias, and apply the same consistent identification, reasonableness, and criteria to any alterations. Using pre- and post-burn NAIP imagery, Lemons first corrected fireline records to follow existing old roads and corrected misclassification errors by distinguishing between pre-existing roads that were maintained as fireline and newly constructed fireline as hand and dozer line. Overlapping ends of adjacent segments and ends that were not correctly adjoined were edited and snapped correctly into place using ArcGIS editing tools. Firelines that were not correctly aligned on the imagery were adjusted to better represent the correct spatial alignment. Any duplicate firelines were removed from the dataset. Misclassifications were reclassed to the correct classification, using notes within the dataset, SBS data, spatial imagery, and reasonableness to identify the correct fireline interpretations.

To test the impacts of fire perimeter on the results of fire effectiveness, we evaluated perimeters from three different sources: original fire perimeters associated with fireline data (FL), perimeters available from Monitoring Trends in Burn Severity (MTBS, https://www.mtbs.gov) and perimeters developed from Soil Burn Severity (SBS), obtained from the Burned Area Emergency Response (BAER) database (https://fsapps.nwcg.gov/baer). Both MTBS and SBS use Landsat satellite imagery with 30-m resolution to estimate fire perimeters (Eidenshink et al. 2007), and SBS incorporates additional field data to improve and verify the accuracy of fire data (Parson et al. 2010).

Gannon et al. (2020) noted that the buffer size around firelines is important to evaluate prior to metric calculations. Designating a buffer zone around firelines allows for minor errors in digitizing and alignment to not bias final metrics. To test for the sensitivity of fireline effectiveness metrics to buffer size, we evaluated a wide range of buffer widths: 15 m, 30 m, 60 m, 90 m, 120 m, 240 m, and 480 m. A final buffer size of 60 m, which represents two pixels, was selected because it allows for minor variation in overlap and metrics do not markedly change between 60 m and larger buffer widths. To evaluate the influence of severity on fireline effectiveness, we used a burned area reflectance classification based on soil burn severity from BAER. Final fireline metrics were summarized by severity class (Unburned/Very Low, Low, Moderate, and High) to evaluate effectiveness in the context of fire severity. Of the 13 fires, 10 fires were associated with SBS layers and used for this analysis.

Task 3: Evaluation of fuel treatment effectiveness within the Interagency Fuel Treatment Decision Support System

Among the main lessons learned from Tasks 1 and 2 is that fuel treatments still represent a minor fraction of North Central Washington landscapes, and as such, cannot be expected to mitigate wildfire effects throughout our study area. Our final task was to integrate what we learned in Tasks 1 and 2 into a decision support tool that managers within North Central Washington could use to evaluate strategic planning options for future fuel reduction treatments. We originally envisioned creating our own decision support tool, but recent advancements in the Interagency Fuel Treatment Decision Support System made it the clear choice for our analysis. We had two main objectives for this task: 1) to create fuel treatment layers that can readily be used by fire and fuels managers for planning purposes, and 2) to evaluate fuel treatment configurations and their influence on burn probability and predicted flame length for priority landscapes within our study area. As part of a 20-year forest health plan for Eastern Washington, the WA DNR has designated 20 priority landscapes for which they will support restoration and resilience work across multiple ownerships (https://www.dnr.wa.gov/ForestHealthPlan). For demonstration purposes, we selected two comparison landscapes that are located within the NCW study area, including Methow/Twisp and Republic.

Development of fuel treatment strategy layer

The fuel treatment layer was designed to provide a shapefile of candidate fuel treatment units, delineated by vegetation type and topography. Our first step was to classify a LANDFIRE Biophysical Setting (BpS) layer across the NCW study area into rescaled 90-m raster layers of non-forest and forested vegetation at high elevation (cold forests dominated by Engelmann spruce, subalpine fir and lodgepole pine) and low elevations (dry-mesic montane forests, dry mixed conifer, and moist mixed conifer). Topographic position was then used to further classify forests into cold-moist (valley, toe slope, and N aspects) and cold-dry (ridge, flat, and S aspects). Similarly low elevation forests were classified into moist mixed conifer forests (valley, toe slope, and N aspects) and dry mixed conifer forests (ridge, flat and S aspects). Low and mid-elevation rangeland pixels were converted to DMC where topography and aspect support higher soil moisture potential, including sites with > 300 mm annual precipitation, north aspects and on valley or toe-slope positions. Potential fuel treatments were then delineated as unique combinations of classified vegetation type, topographic class, and aspect class (**Table 3**).

Table 3: Classes of vegetation, topography, and aspect that are the basis of strategic fuel treatment layers.

Vegetation Class		Topography Class		Aspect Class	
1	Cold forests, 2 Dry and moist mixed conifer forest	1	Valley	0	Flat (no aspect)
10	Water, 11 Bare ground	2	Valley-like	1	North aspects
12	Grassland 13 Shrubland	4	Mid slope		
14	Hardwood 15 Alpine meadow	5	Ridgelike		
16	Juniper				
20	Dry mixed conifer				
30	Moist mixed conifer				

IFTDSS simulations

The latest version of IFTDSS (https://iftdss.firenet.gov) was used to develop planning scenarios for the Methow Valley and Republic priority landscapes. Based on the potential treatment layer, we randomly selected treatment units representing a total of 10%, 20%, 30%, 40%, 50% and 60% treated area within each priority landscape. To develop scenarios within IFTDSS, we first created a base landscape file, selecting the LANDFIRE 2012 fuel model layer to represent fuel conditions prior to the 2014 and 2015 wildfire seasons. We then imported shapefiles representing the fuel treatment layers and used these as landscape masks to create custom IFTDSS landscapes for each treatment scenario. We assumed that all units had the same fuel reduction treatment. Using the Landscape Edit tool and shapefile masks for each treatment scenario, we first selected the Default IFTDSS treatment edit rule: heavy thin followed by prescribed burning. We then customized the surface fuels within each treatment unit to represent 1 yr post-fire (fuel model TL1, Scott and Burgan 2005). Because our study area landscapes are dominated by lower elevation forests, we did not vary fuel treatment by forest type, but future scenarios could readily tailor treatments for high (cold) vs low elevation forests (dry and moist mixed conifer forests).

We tested two different summer wildfire scenarios using the IFTDSS landscape burn probability module. Canopy fuel moisture was set to 80%, and the Scott and Reinhart crown fire module was selected. Surface fuel moistures were assigned to be very dry, representing extreme fire danger: 1hr – 3%, 10hr – 4%, 100hr – 5%, live herb – 30%, live shrub (woody) – 60%. Fuel conditioning was available for both study areas, and we elected to select "Extreme" fuel conditioning. To compare the effect of wind speed on predicted burn probability and conditional flame lengths, wind was input as 35 mph in the first set of simulations and 15 mph in the second set of simulations.

Results and Discussion

Task 1: Burn severity analysis

Carlton Complex

The 2014 Carlton Complex is one of the largest single wildfires in Washington state history and at the time, burned under unprecedented fire weather. Of the 102,000 ha burned in the Carlton Complex, 68,000 ha burned in a single burn period, driven by maximum wind gusts > 8 m sec^{-1}. During this extreme fire spread event, wind-driven fire brands ignited fuels well in advance of the flaming front, and column-driven extreme fire behavior dominated. Approximately 40% of the area burned was forested, and within forested landscapes, fuel treatments were put to the ultimate test.

Past studies have questioned whether bottom-up controls including fuels and topography are important during extreme weather events or if top-down climatic and fire weather controls dominate. Some studies suggest that fuel reduction treatments are ineffective at reducing fire behavior and effects under extreme weather conditions (e.g., Schoennagel et al. 2004). In crown fire systems, studies such as Turner and Romme (1994) and Bessie and Johnson (1995) suggest that drought and extreme fire weather can reduce thresholds to burning across a range of fuel types and forest ages, predisposing forests to extreme fire behavior.

Because of this, we were particularly interested in evaluating if and how fuel reduction treatments mitigated fire severity during the wind-driven progression intervals. Through our fire severity modeling that assessed top-down and bottom-up drivers of severity, we found that fire weather certainly reduced the effectiveness of recent fuel reduction treatments but that effects were variable and site dependent. Treatments including thinning and underburning, underburning only, and past wildfires tended to reduce fire severity overall but were much less effective under extreme weather (**Figure 4**). However, outcomes were strongly dependent on landscape position relative to prevailing wind and fire spread. Fuel reduction treatments located on windward slopes were likely exposed to preheating and ignition from column-driven fires. However, leeward slopes offered some protection and were associated with reduced fire severity, particularly in prior treatment areas that involved prescribed burning or past wildfires.

Previous studies have found that fuel treatments involving broadcast burning of surface fuels (e.g., past wildfires, prescribed burns and thinning or clearcutting with prescribed understory or broadcast burns) are generally more effective than thin-only or thin and pile burn treatments (see Stephens et al. 2012, Kalies and Kent 2016 for reviews). Our results corroborate these studies but offer a rare evaluation of how treatments fared on wind-driven progressions compared to those that burned under milder weather conditions. All treatment areas burned with lower proportions of unburned and low severity fire during early fire progressions associated with extreme fire weather and behavior (**Figure 5).** Final SAR models suggest that ThinUB treatments were the most effective, followed by thin-only and UB-only treatments (**Table 4**). Regardless of type, fuel treatments, including thin-only treatments, were more effective in later progressions under milder fire weather conditions, and differences between treatments were less pronounced. Some treatment types such as clearcut and broadcast burn and thin and pile burn were not significantly related to fire severity, which is likely due to low sample size, but treatment type could have also contributed to the lack of significance.

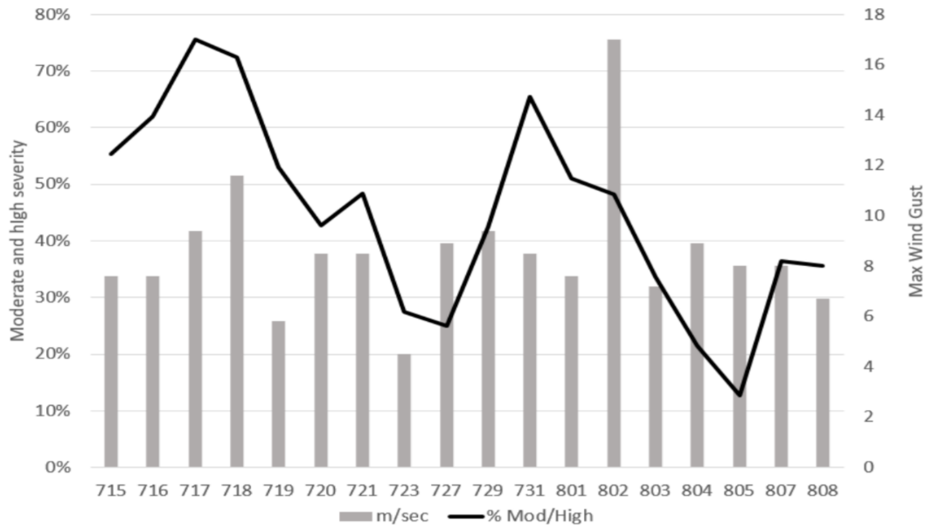

Figure 4: Proportion of fuel treatments with moderate and high severity pixels across individual fire progression days of the 2014 Carlton Complex. Maximum wind gust is also displayed as vertical bars (secondary y axis).

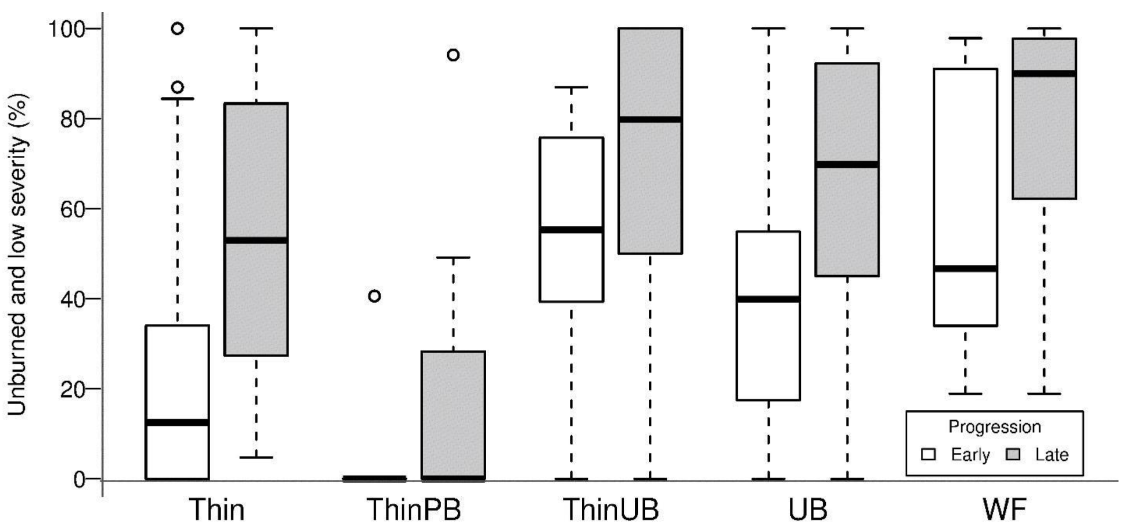

Figure 5: Box plots of the percentage of pixels in treatment units categorized as unburned and low severity by treatment type for early progression dates ranging from 7/15 to 7/18 and later progression dates ranging from 7/19 to 8/10. Treatments include thin only (thin), thin and pile burn (ThinPB), and thin and prescribed underburn (ThinUB), prescribed underburn only (UB) and past wildfire (WF). Clearcut and broadcast burn (CCBB) was not included in this comparison because this treatment type was only present in the North study area.

Table 4: Estimates, standard error and p values (P) of simultaneous autoregression models (SAR) of fire severity by study area. Treatment types include clearcut and broadcast burn (CCBB), thin only (thin), thin and pile burn (ThinPB), thin and prescribed underburn (ThinUB), underburn (UB) and past wildfire (WF). CanCov = Canopy cover, Cover Types include bare ground (Bare), developed/roads (dev), dry mixed conifer forest (DMC), moist mixed conifer forest (MMC), ponderosa pine forests (PP), riparian vegetation (Rip), and shrublands (Shrub).

Variable	Carlton North	SE	P	Carlton South	SE	P
Intercept	152.56	16.52	**< 0.0001**	272.47	7.45	**< 0.0001**
Treatment						
CCBB	-2.92	2.38	0.2204			
Thin	-5.64	1.64	**0.0006**	-6.94	3.43	**0.0428**
ThinPB	1.97	1.97	0.3174	-0.30	4.12	0.9419
ThinUB	-9.36	2.11	**< 0.0001**	-16.26	4.48	**0.0003**
UB	-5.65	1.64	**0.0006**	-1.10	2.25	0.6251
WF	-2.66	2.43	0.2737	-5.95	1.64	**0.0003**
CanCov	0.28	0.01	**< 0.0001**	-0.06	0.01	**< 0.0001**
Cover Type						
Bare	-	-	-	-8.03	0.56	**< 0.0001**
Dev	-	-	-	-8.18	0.98	**< 0.0001**
DMC	-	-	-	-0.20	0.88	0.8224
MMC	-	-	-	1.08	0.73	0.1384
PP	-	-	-	1.60	0.87	0.0674
Rip	-	-	-	-3.03	1.53	**0.0473**
Shrub	-	-	-	-1.83	0.38	**< 0.0001**
Elev	0.29	0.01	**< 0.0001**	-	-	-
Valley1200	-	-	-	-1.02	0.07	**< 0.0001**
MaxTemp	-	-	-	0.47	0.21	**0.0231**
SolRadMax	-0.03	0.00	**< 0.0001**	-	-	-
WNSpeed	0.74	0.11	**< 0.0001**	-	-	-

As with SAR modeling, our Random Forest analysis also demonstrated fuel treatments were generally associated with lower fire severity. Overall, Thin, ThinUB and UB treatments, along with past wildfire (WF), appeared to be the most effective at mitigating fire severity. High local importance for fuel treatments in the RF models were identified in the North study area, even during burn periods with large fire growth. Effective treatments in the North study area corresponded roughly with leeward south and southwest facing aspects which may have been partially sheltered from the strong prevailing winds coming from the north and northwest. This finding provides some evidence that lower fire severity was associated with treatments situated on leeward slopes in relation to the predominant wind direction during wind-driven fire progressions. Leeward treatments may have slowed fire growth during this period but did not appear to be absolute barriers to fire spread.

There is evidence that a set of fuel treatments, located along a leeward ridge in the southeastern section of the North study area, mitigated fire severity and contributed to a large, unburned island between the North and South study areas. More research is warranted in identifying treatment effectiveness as a function of terrain positioning in relation to the prevailing winds during fire spread. Interestingly, in the North study area, the RF methods identified high local importance for the treatment variable where no treatment occurred. This possibly indicated that the lack of treatment led to higher severities than would have otherwise been predicted if the area had been treated and may provide support for directing future fuel treatments (**Figure 6**).

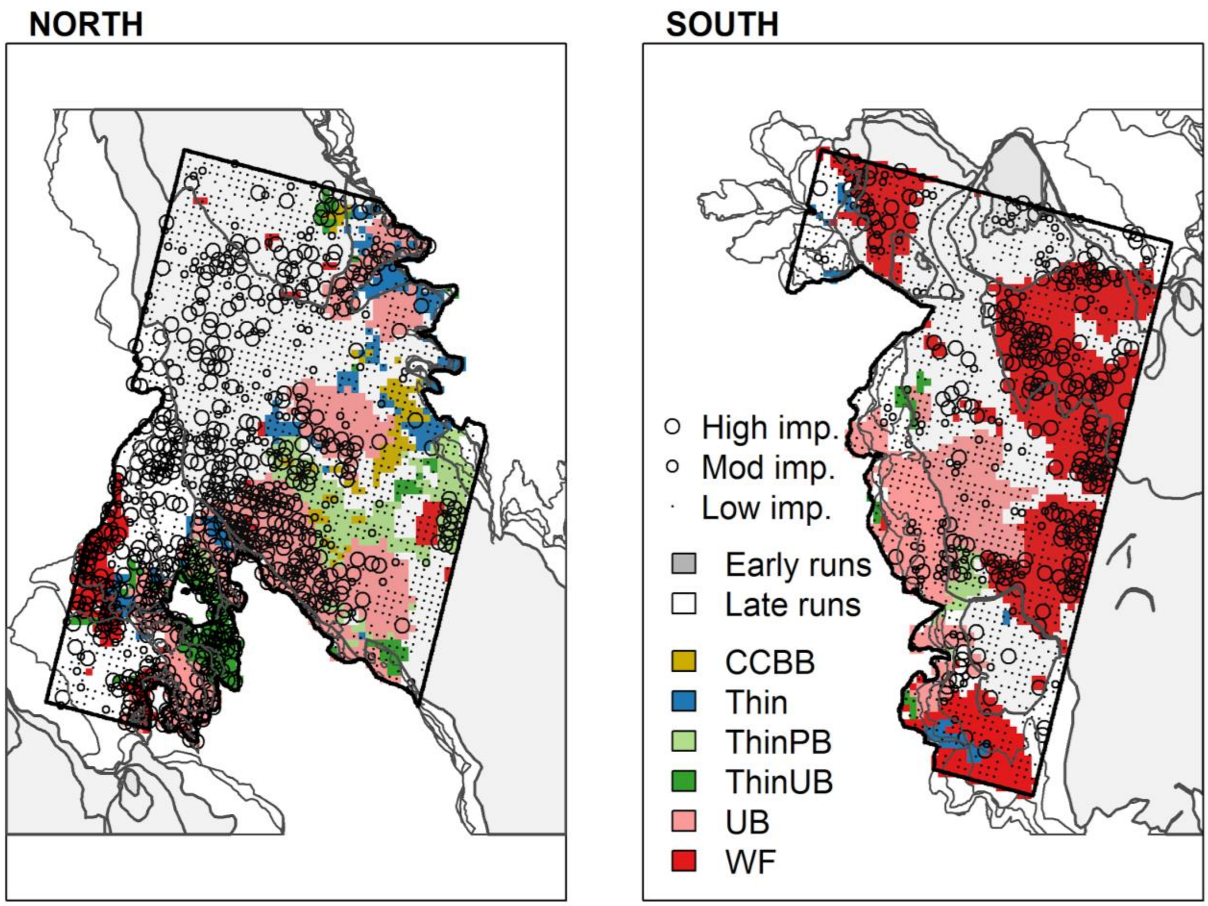

Figure 6: Map of local variable importance for the treatment predictor variable from Random Forest modeling. Local importance values range between 0-1 and classes are: High (0.75-1.0), Moderate (0.5 – 0.74), and Low importance (0-0.49). Treatments are: clearcut and broadcast burn (CCBB); thin-only (Thin); thin and pile burn (ThinPB), thin and prescribed underburn (ThinUB), prescribed underburn only (UB) and past wildfire (WF).

With longer wildfire seasons and a growing incidence of extreme fire weather events, planning for wind-driven fire growth in drought-impacted forests is increasingly necessary. As fire and fuels managers evaluate options for increasing landscape resilience and resistance to future climate change and wildfires, strategic placement of fuel treatments may be guided by retrospective studies of past large wildfire events. Our results suggest that during strong wind-driven fire spread, fuel treatments located on leeward slopes of prevailing winds tended to have lower fire severity. The wind-driven progression on July 17-18 during the Carlton fire originated from a weather system that moved from the Pacific Coast to interior Washington State and was funneled through the Methow Valley, leading to strong, directional winds (**Figure 7)**. These winds, as well as the wind patterns observed during the 2006 Tripod Complex, and large fires of 2015 in north-central Washington State, were typical of summer wildfire weather. This suggests that modeling of predominant summer wind characteristics can be a useful tool in strategic planning of landscape treatment prioritizations (Hessburg et al. 2015).

Global fire severity analysis: 2014 and 2015 fires of north-central Washington

Although analysis of fire severity within large wildfires is common in the literature (e.g., the 2013 Rim Fire or 2014 Carlton Complex Fire), final burn scars are comprised of a series of fire progressions, each with a unique combination of fuels, weather and biophysical variables. As such, we evaluated drivers of fire severity across all large fires that burned during the 2014-2015 season (global model), individual fire events, and major fire progression days. As with the Carlton Complex analysis, final models in this analysis were selected to include the variables that had the highest explanatory power. These included a range of predictor variables, including day-of burn weather, past treatment type and time since treatment, landform indices, fuel moisture and biophysical indices, vegetation type, and canopy base height.

Following Cansler et al. (*in press*), we also evaluated drivers of fire severity for first-entry fires representing long unburned pixels (**Figure 8A**), compared to reburn areas (**Figure 8B**). As part of the JFSP-funded NEWFIRE study (JFSP Project 16-1-05-24), they evaluated drivers of wildfire severity for all fires in north-central Washington that burned between 2001 to 2019. Our current study is highly complementary to their recent study because it compares models built globally for all fires to those built on individual fire events and daily progressions. This allows us to better understand the unique combination of conditions that conspired to produce some of the largest fires on record in the region. The motivation for this approach was that drivers of wildfire severity are multi-dimensional, multi-scaled, and nonstationary such that the specific combinations of features at a given point in space and time are complex and unique to a given fire and given fire progression within a fire. Modeling these separately allows for a more detailed look at how the primacy and direction of influences varies across a fire footprint. This is a particularly powerful approach to take when evaluating large wildfires, which are traditionally thought to be a result of top-down drivers and where bottom-up drivers play a minimal role and where reliance on global variable importance statistics may be biased towards that result (e.g., Turner and Romme 1994).

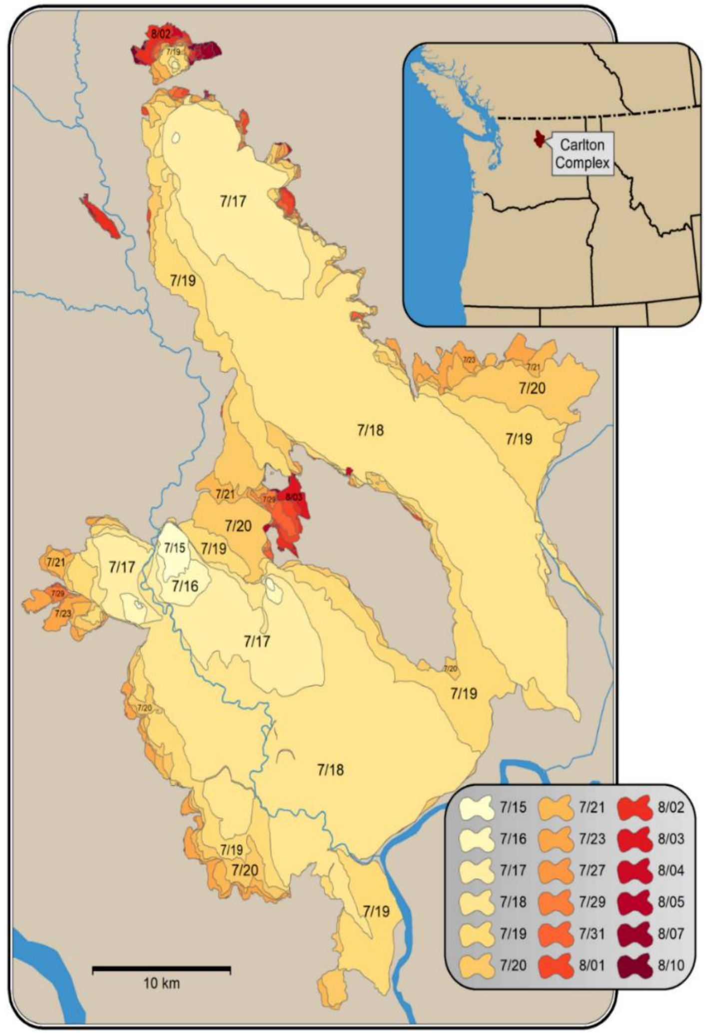

Figure 7: Fire progression intervals of the 2014 Carlton Complex fire. A total of 68,000 ha burned in the two represented burn perimeters from 8 am on 7/17 to 1 am on 7/18.

Top-down drivers and their variability

Through our detailed investigation of large fire events from 2014-2015, global, individual fire, and individual progression models showed that first-entry fires were largely driven by top-down climatic and fire weather drivers compared to areas that reburned (**Figure 8**). Across all fires, many of the biophysical variables suggested that higher elevation, montane forests were associated with higher fire severity. These multi-layered mixed conifer forests are associated with lower canopy base heights and higher live and dead fuel moisture than lower elevation forests. Climatic water deficit (30-yr normal) showed a negative relationship with fire severity, suggesting that cooler and moister climates had higher severities in general. Although it may seem counterintuitive at first that these biophysical characteristics, including higher site moisture, are associated with higher severity, high severity fire is more common in montane forest types due to more continuous forest cover, layered forest canopies, and the prevalence of thin-barked tree species that are more readily killed by fire (Hessburg et al. 2019).

Not surprisingly, the global model also showed a strong positive relationship between maximum temperature and fire severity and a correspondingly strong negative relationship with maximum relative humidity. Maximum wind gust speed and direction were also highly correlated with high severity. Modeled relationships between top-down climatic controls and fire severity have also been found in previous large fire studies (Cansler and McKenzie 2014, Kane et al. 2015, Povak et al. 2020, Prichard et al. 2020). However, the response of fire severity patterns to top-down drivers varied across individual wildfires and across progression days. For example, maximum temperature during a fire exhibited a negative relationship with fire severity across many of the individual fires and progression days, counter to the global model. This variable in particular had a non-linear relationship with fire severity in the global model where severities were moderate for cooler temperatures, lowest for temperatures near average temperature, and highest for the highest temperatures on record. Negative relationships between maximum temperature and fire severity occurred for individual fires and fire progressions that did not experience warm temperatures compared to all other fires and therefore did not exhibit the increase in severity associated with the warmest temperatures. This highlights the importance of using multiple lines of inference when evaluating model results. For reburned pixels, top-down variables were less important compared to first-entry fires (**Figure 8B**). Similar trends were found for reburns in relation to climate and fire-weather variables as was found for first-entry fires, but their overall importance was lower.

Maps of local importance also reveal interesting patterns in the variability of top-down drivers. For example, fire weather during the North Star Fire exhibited considerable variation in its relative influence on fire severity (**Figure 9**). The large patch of high severity in the center of the fire appeared to have been driven largely by fire weather, but towards the fire perimeter, fire weather had a mitigating influence on fire severity.

Bottom-up drivers and their variability

Bottom-up controls provided by fuels/vegetation, topography and past wildfire and management footprints were strong for both reburn and first-entry fires. NDMI was a lead driver of reburn severity and led to linear increases in fire severity, suggesting that higher levels of live fuel moisture led to higher severity. Although this result may seem counterintuitive at first, NDMI provides a measure of the density of living leaves and is well-correlated with the live leaf area (Goulden et al. 2019). Live fuels generally have high thresholds to burning given their high foliar moisture content. Therefore, when these forest patches do burn, it is generally at higher severity given the heat requirements to ignite dense live fuels. This result may be indicative of areas where crown fire is being sent from neighboring pixels, indicating that preheating of live fuels may usurp other dominant controls on fire severity and suggesting a role of spatial autocorrelation in driving fire patterns. Furthermore, high NDMI is associated with higher elevation, multi-layered mixed conifer forests that generally experience high severity fire regimes. Parks et al. (2014b) similarly found increased fire severity with increasing NDVI, a spectral index similar to NDMI but a more direct measure of greenness. The authors attribute this relationship to increases in biomass due to increased moisture and fuel loads along an elevational gradient. Similar results were found in Dillon et al. (2011) where fire severity increased with increasing biomass along an elevation gradient in the Rocky Mountains, USA.

Fire severity was negatively related to canopy base height and suggests that higher CBH nearly always led to lower fire severity. Increasing CBH is a fundamental goal of fuel reduction treatments to reduce the ladder fuels and the probability of fire spread into the canopy (Prichard et al. 2021). Our results support the utility of fuel reduction treatments towards that end. The variable NDVI_NF_750 (NDVI for non-forested areas within a 750-m window around a given 30-m pixel) indicated that fire severity

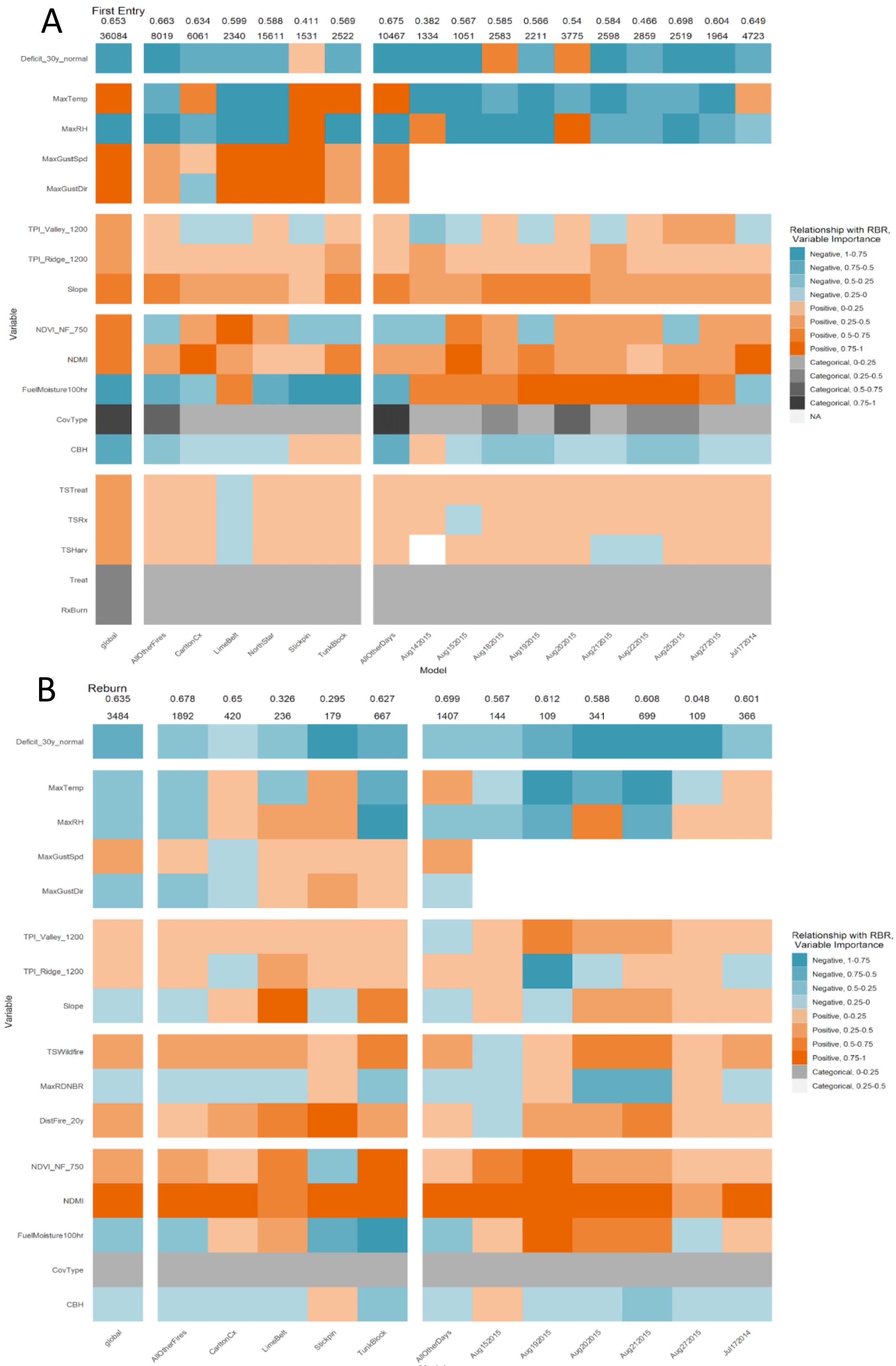

Figure 8: Heat map showing the relative strength of predictor variables on Relativized Burn Ratio in pixels that A) were long unburned (first entry) and B) had a recent prescribed fire or wildfire and were reburned by the 2014/2015 wildfires. Variable definitions are listed in Table 3. The first row of numbers are R2 values for each of the RF models and the second row is each model's sample size.

increased with increased coverage of grass, shrub and other early seral vegetation. Fires carried by non-forest fuels often have high rates of spread, but low flame lengths. However, if dense enough, these fuels appear to be able to spread fires into forested areas and cause an elevated level of severity.

Topography also played an important role in driving fire severity patterns. Percent slope was a main driver, and fire severity generally increased with increasing slope. This relationship declined around 30% slope, and for some fires severity was lower for the steepest slope, sometimes leading to a negative relationship. Often, steep slopes are associated with non-forest and non-burnable substrates due to thin soils and exposed rock that may restrict fire spread and severity locally. The contribution of topography variables to explaining fire severity patterns in previous work has been mixed. This is largely since the influence of topography, a key bottom-up control, is likely diminished under extreme fire weather conditions (Dillon et al. 2011) and is a strong determinant of vegetation and fuel conditions, which are also key drivers of severity patterns (Parks et al. 2014b). Parks et al. (2018a) found that out of 19 ecoregions, topography had the lowest variable importance and the authors attribute this to topography's indirect effect on fuels, which they had modeled directly using spectral indices. Our finding of a strong role for topography suggests that bottom-up factors can still influence severity patterns even for the largest events. In the North Star example (**Figure 9**), topography largely had a mitigating influence on fire severity, but some topographic features - largely ridges and valleys - appear to have increased severity in certain areas.

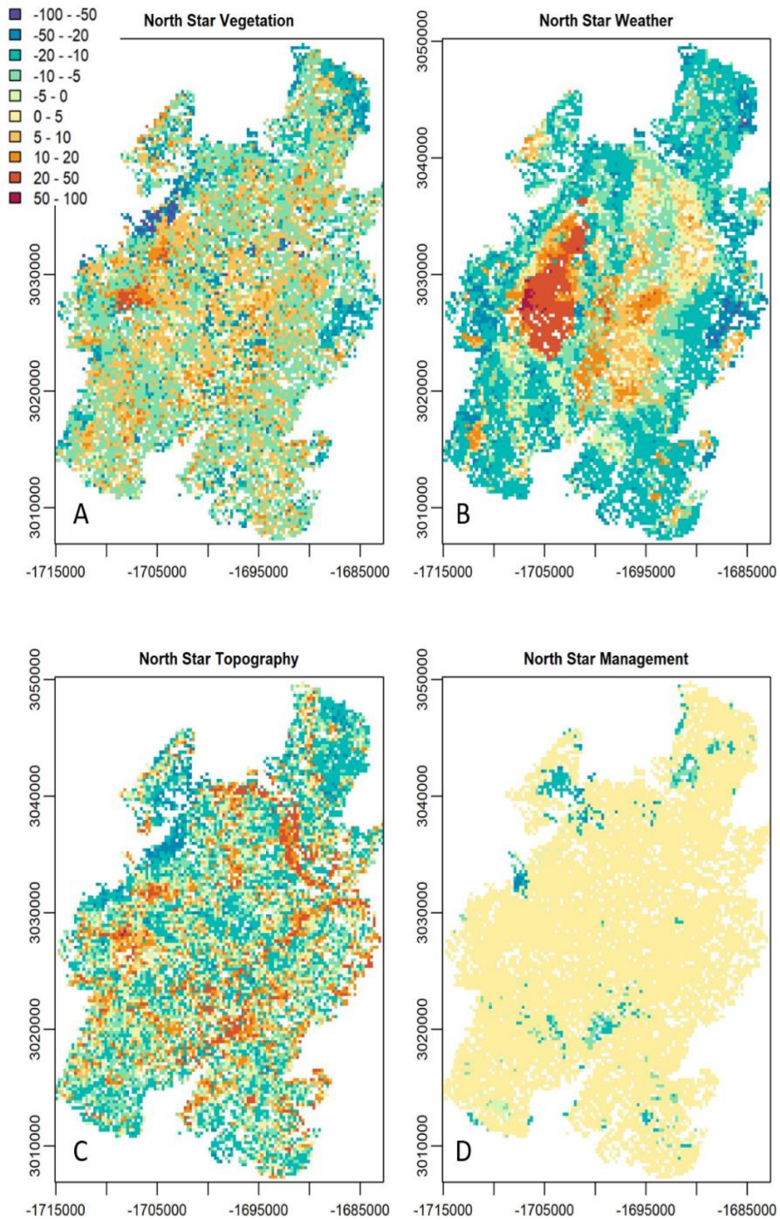

Figure 9. Spatial distribution of local importance values for the North Star fire for predictor variable groups: A) vegetation/fuels, B) weather, C) topography, and D) management.

Past fuel reduction treatments exhibited overall low importance due to their scarcity on the landscape compared to the area burned in 2014-2015. However, a consistent positive relationship was found between time since treatment and fire severity, suggesting that treatments can make a difference in reducing wildfire severity, but this effect wanes over time. Similarly, previous wildfires displayed strong controls on fire severity in reburns. Specifically, fire severity increased with time-since-last fire and with distance to previous fire edge. Past fire severity was also a main driver and revealed a negative relationship between past severity and current. Management in the North Star Fire is evident in **Figure 9D**, where treatments, while sparsely dispersed throughout the fire, led to an overall decrease in fire severity compared to surrounding untreated areas. Povak et al. (2020) showed similar results in the Rim

Fire that burned in 2013 in the southern Sierras. Their work corroborated field assessments of fuel treatment effectiveness during the fire (Lydersen et al. 2017).

Task 2a: Firefighting lessons learned

During the 2014 and 2015 wildfire seasons, available resources for fighting wildfires in north-central WA were limited, and local fire crews and resource managers needed to initially respond to the many wildfires. Because of this situation, we were able to speak with many local managers who served on wildfire response and document the following lessons learned about how past fuel treatments were used to promote a safe and effective wildfire response. Subsequent wildfire seasons also put many fuel treatment areas to the test, and we were able to compile several more lessons learned from these wildfires. Specific examples are summarized on our project website.

Table 5: Examples of past fuel treatments used in wildland firefighting operations.

Wildfire	Fuel treatment	Lessons learned
2014 Carlton Complex	Leecher Mountain Underburn	A large thin and underburn conducted in 2001 and located on a leeward slope, supported a flanking fire that backed downhill and allowed firefighters to successfully defend the "doughnut hole" which had a series of fuel reduction treatments that provided more defensible space for firefighting operations when the weather permitted access.
2015 North Star Fire	Lost Units	Recent (2014) prescribed burn unit was used for a low intensity burnout that acted as a summer Rx burn. One of the lessons learned is that with patience and backing strip fires, summer prescribed burning can be accomplished at the height of fire season to create defensible space and further maintain treatments.
	Aeneas Valley	Network of roads and treatments helped to corral the North Star Fire to the east away from Aeneas Valley on the outskirts of Tonasket, WA.
2018 Boyds Fire	Sherman Creek Wildlife Area prescribed burn units	Past thinning and prescribed burning made the Boyds Fire transition to the surface and allowed the fire to be contained and saved homes, powerlines near Kettle Falls, WA.
2018 McLeod Fire	Eight Mile treatments	A series of past thinning and underburn treatments were used to support burnout operations along the Eight Mile Rd in the 2018 McLeod Fire. Crews commented about how the previous treatments gave them much more decision space than along the Twisp River drainage within the concurrent Crescent Mountain Fire.
2021 Cedar Creek Fire	Virginia Ridge Timber Sale	WA DNR conducted a commercial thin in 2019 on Virginia Ridge (Methow Valley). Both units were subsequently burned in the 2021 Cedar Creek fire with variable effects.

Task 2b: Fireline Effectiveness

As the incidence, size and severity of wildfires increases throughout the western US, assessments of firefighting costs and the effectiveness of direct suppression are being made. Although the cost per unit area of large wildfires is lower than small fires, large, summer wildfires are responsible for rising firefighting costs, particularly in forested areas and under extreme weather (Gebert et al. 2007, Calkin et al. 2015). Direct suppression is not only expensive but can also have ecological impacts, including soil erosion and exposure to invasive species that necessitate post-fire rehabilitation (Keeley 2006). Assessment of fireline effectiveness is therefore important for informing how the type of fireline (bulldozer, handline, and roads as completed line), biophysical setting, and how severely fires burn influences firefighting outcomes and if investment in suppression paid off. Ideally, an analysis of firelines would also include strategic networks of fuel reduction treatments. However, to date, fuel treatments are still a minor feature within north-central Washington landscapes, and it was not possible to combine these analyses.

We first assessed the Gannon et al. (2020) method to determine if fireline data could be used directly from firebox records or if quality assurance and quality control (QA/QC) measures were needed to correct for digitizing and misclassification errors. We found several inconsistencies that suggest that some broad QA/QC should be conducted prior to evaluating fireline effectiveness. The largest errors were associated with the Kettle Complex fires (Graves, Renner and Stickpin) in which many misclassification errors between road as completed line and dozer lines were discovered. Once misclassification errors were corrected, estimated length of firelines dramatically increased for the Kettle Complex fires: Renner (51.8%), Stickpin (65.7%), and Graves Mountain (56.6%). The total length of firelines slightly decreased in the Carlton Complex due to duplication of lines which were drawn on top of each other. However, most fireline edits did not lead to a significant increase or decrease in total fireline length and thus did not substantially change fireline metrics. Our results suggest that fine scale editing of firelines is likely not needed because edits did not substantially influence fireline length estimates, and the buffer width around firelines allows for some inaccuracies to exist without affecting the results. As detailed in Gannon et al. (2020) buffer size is an important factor in fireline effectiveness. Buffer size has a marked influence on fireline effectiveness for the three types of fireline we evaluated. Because we are working with 30-m imagery, and fireline errors were mostly fine scale, a 60-m buffer was determined to be a reasonable selection for calculating effectiveness metrics.

Effect of perimeter source on fireline effectiveness metrics

Most of the wildfires that we evaluated had three potential sources of final fire perimeters, including the original geospatial records from firefighting records (FL), MTBS, and SBS (**Table 6**). Inconveniently, there were sometimes major differences in overall fire area and fire perimeters associated with these records. Most notably, the 2017 Diamond Creek Fire had the largest differences likely due to the burned area near the firelines being only recorded within the fireline activity area while the MTBS and SBS perimeters included additional wilderness northward across the US/Canada border. Our comparison of fire perimeters again underscores the importance of careful review to ensure consistency in datasets prior to calculating fireline effectiveness metrics across multiple fires.

Because total fire perimeter is used in calculating metrics, fireline effectiveness is highly dependent on fire perimeter source. Perimeters based on Soil Burn Severity were not available for all fires (9 Mile, North Star, and Tunk Block), but it is generally the most reliable source for final fire perimeters and is also associated with somewhat higher overall fireline effectiveness, based on the held to total fireline constructed ratio (HTr) (**Figure 10**). MTBS dissolves unburned patches within supported fire perimeters. For example, the 2014 Carlton Complex contains a large, unburned island; estimated fireline effectiveness can be markedly reduced based on the MTBS perimeter layer (**Figure 11**).

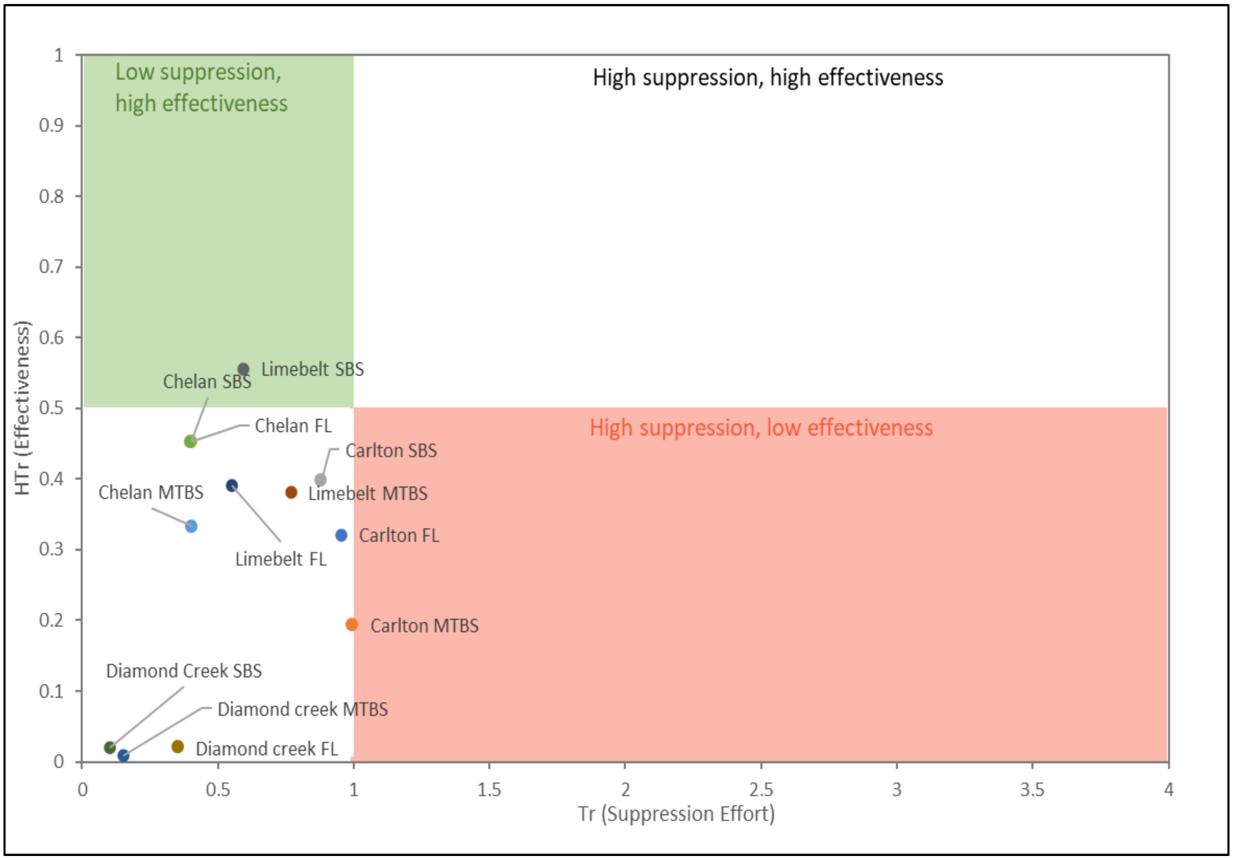

Figure 10: Comparison of two fireline effectiveness including an overall fireline effectiveness metric (Held fireline length to Total Fireline length, HTr) vs. suppression effort (total fireline length, Tr). Only large fires that include all three source perimeters are displayed.

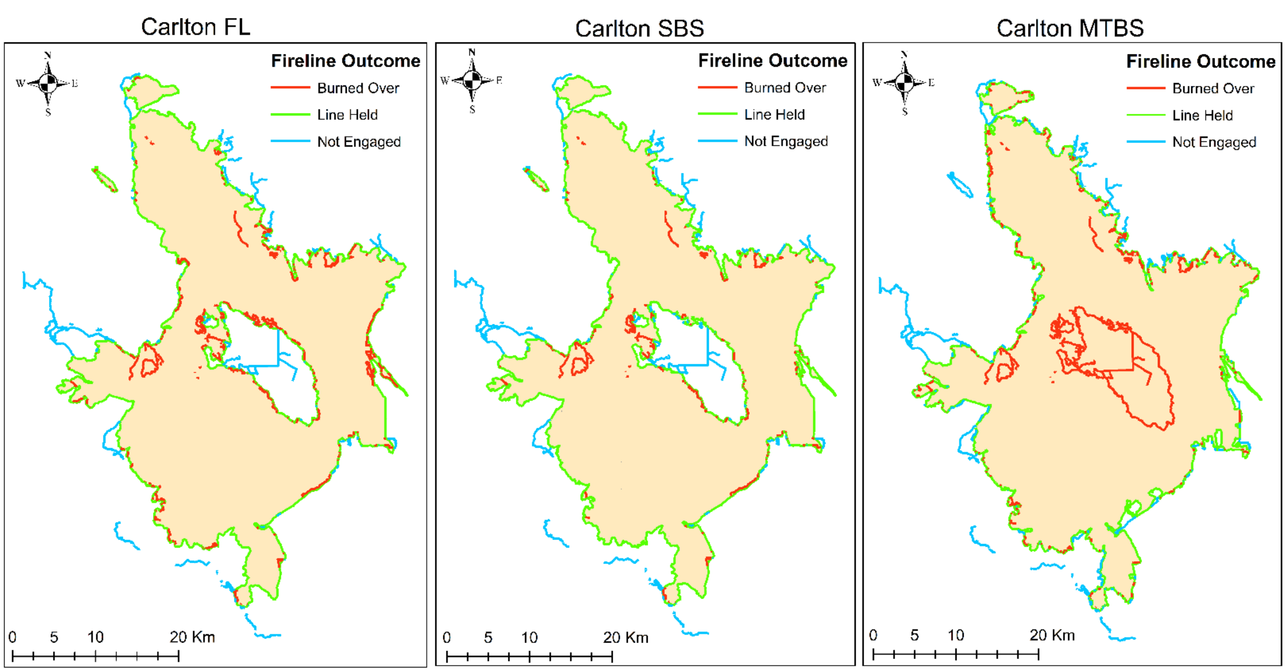

Figure 11: Fireline outcomes within the 2014 Carlton Complex fire, comparing three source perimeters including the original fireline dataset (FL), Monitoring Trends in Burn Severity (MTBS), and Soil Burn Severity (SBS).

Fire Severity and Fireline Effectiveness

Across all wildfires that we evaluated, areas that burned with low and unburn/extremely low severity are associated with low suppression effort, but firelines within these areas were highly effective (**Figure 12**). Moderate severity areas also tended to have low amounts of firelines but firelines were less effective. High severity areas are associated with greater suppression effort, with the effectiveness ranging from highly effective to low effectiveness. Completed dozer lines were the dominant fireline type and had a much greater engagement, held, and burned over length. As such, the total fireline engaged, held and burned over were all greatest for completed dozer lines.

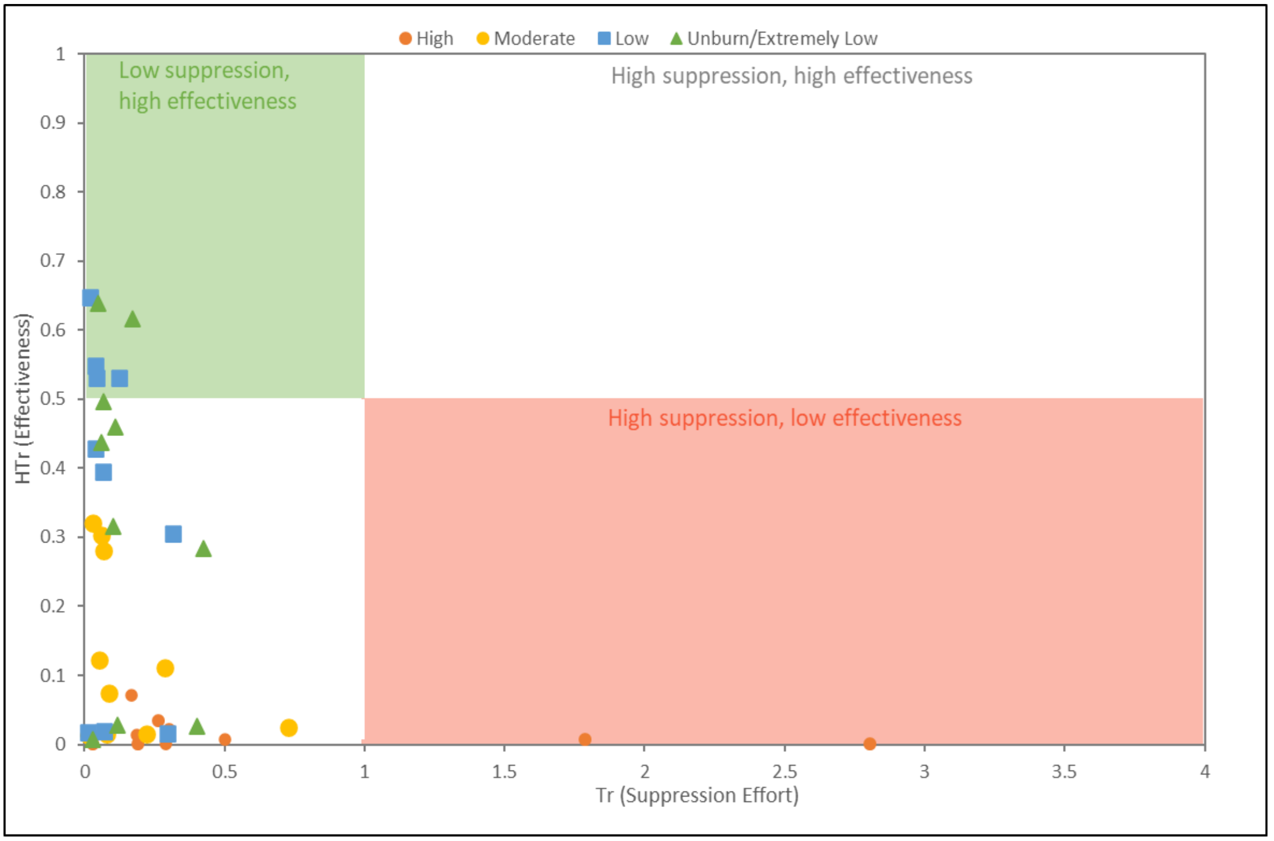

Figure 12: Influence of fire severity on fireline effectiveness where HTr is a measure of overall fireline effectiveness metric and Tr is a measure of suppression effort.

Final Metrics

Because SBS appeared to be more accurate than perimeters included with fireline records or MTBS perimeters, which didn't factor in unburned interior perimeters, we opted to use SBS as the most accurate source of perimeter data. However, because SBS was not available for all wildfires, we used the original perimeters provided with fireline datasets for wildfires lacking SBS layers. Final metrics are summarized in Table 9. These metrics of fireline effectiveness that can be used to evaluate not only the overall investment in fireline construction but also relative measures of efficacy including the ratio of fireline that was engaged by wildfires and of that, how much of the fireline length held. Finally, the ratio of how much fireline held vs the total investment into fireline can be used as an overall effectiveness metric.

Suppression effort (Tr): The ratio of total fireline length compared to wildfire perimeter (Tr) provides an estimate of the relative investment for a given wildfire (**Table 7**). Of these, the Kettle Complex fires and 9-Mile fire are outliers, with total fireline length that exceed wildfire perimeters. However, most fireline metrics fall below 1.0 and are considered within a "low" category of suppression effort by Gannon et al. (2020). The Kettle Complex fires were likely outliers because wildland fire planners treated the fires as a single complex and interconnected firelines across the three geographically distinct fires. The 9-mile fire, which was the smallest fire that we considered in our study, had firelines, including dozer lines and road as completed line, that completed encircled its perimeter.

Engaged fireline (Er): Er is the ratio of engaged fireline versus total fireline length. Of the 2205 km of fireline, a total of 972 km (44%) was engaged by the wildfires. However, this metric ranges widely across fires with high engagement (over 70%) in 9 Mile, Lime Belt, Tunk Block and Twisp River. These wildfires, which represent a wide range in fire sizes, tend to have more non-forest than forest vegetation where fireline would be expected to be more effective. Notably, low levels of engagement (under 50%) were found in Diamond Creek, Graves Mountain, North Star, Renner, Stickpin, Wolverine Complex, and Uno Peak. Of these, Diamond Creek and the Wolverine Complex burned mostly in wilderness areas, and it appears that firelines were constructed as contingency lines in case wildfires burned into roaded and WUI areas. The Kettle Complex fires had an extremely high level of suppression effort, associated with a network of roads and dozer lines that connected the geographically separated wildfires. Many of the more distant lines were never engaged by the wildfires.

Held fireline (HEr): HEr is a ratio of held fireline versus total engaged fireline and provides a measure of how effective firelines were as actual barriers to fire spread. Not surprisingly, there was a wide range in effectiveness from 100% to 47%, which strongly corresponds to fire severity. Overall, areas that burned in UB/Low severity fires had much higher HEr than those areas that burned at moderate and high severity. Although severity is calculated post-fire, these findings may still be informative for future prioritization of firelines. Where fires are expected to burn at higher severity (e.g., dense, mixed conifer forests), firelines are likely to be less effective. These results are not novel and are well supported by standard nomograms of predicted fire behavior in wildland fuels and firefighting options (Rothermel 1983). However, in future studies, it would be interesting to review how often firelines are constructed in wildland fuel complexes that are not likely to hold and what the actual outcomes are. Geospatial records of firelines could also be improved to differentiate between firelines that are constructed during mop-up operations vs. those that are constructed in advance of a progressing fire. The held to engaged fire ratios was over 0.5 for most wildfires, indicating a relatively high success rate, which was likely bolstered by inclusion of many firelines that were constructed during mop-up operations.

Overall fireline effectiveness (HTr): HTr is a ratio of held fireline length to total fireline length, which provides a summary metric of how well firelines performed relative to the level of investment into firelines. For wildfires with a very low engagement ratio, the HTr is also very low, including wildfires that burned mostly in roadless areas that had more distant firelines (2015 Wolverine and 2017 Diamond Creek) as well as the Kettle Complex fires. Among the wildfires with the most effectiveness are 9 Mile, Carlton Complex and Chelan Complex. The 9 Mile fire burned in grass and shrub steppe, and firefighting crews took advantage of existing roads to contain the small fire. The Chelan and Carlton Complex fires also had high percentages of nonforest, which likely enabled more effective firelines. However, based on the fireline records that we have, we cannot distinguish between firelines that were constructed in advance of a progressing fire and those constructed during mop up operations. In the future, well attributed fireline records that record the construction date would greatly refine estimates of overall fireline effectiveness.

Table 6: Wildfire statistics (area, perimeter) and metrics including burned over (BO), held (Held), not engaged (NE), total fireline (TL) and total engaged (Engaged) distances. Fireline metrics include total fireline length to fire perimeter ratio (Tr), engaged fireline to total fireline ratio (Er), held to engaged fireline ratio (HEr), and held to total fireline ratio (HTr), reported for three perimeter sources, including original fireline dataset (FL), soil burn severity (SBS), and Monitoring Trends in Burn Severity (MTBS).

		Fire area and perimeter		**Fireline distances**					**Fireline metrics**			
Fire	**Type**	**Area ha**	**Perim km**	**BO km**	**Held km**	**NE km**	**TL km**	**Engaged km**	**Tr**	**Er**	**HEr**	**HTr**
2014 Wildfires												
Carlton Complex	FL	104,453	403.2	116.6	123.6	145.1	385.2	240.2	0.96	0.62	0.51	0.32
	SBS	103,490	437.9	77.3	153.4	154.5	385.2	230.7	0.88	0.6	0.66	0.4
	MTBS	111,730	387.6	179.9	74.7	130.7	385.2	254.5	0.99	0.66	0.29	0.19
2015 Wildfires												
9 Mile	FL	1,907	26.8	1.1	21.8	4.6	27.4	22.9	1.02	0.83	0.95	0.79
	MTBS	2045	27.6	6.9	17.6	2.9	27.4	24.5	0.99	0.9	0.72	0.64
Chelan Complex	FL	35,800	336.4	10.3	60.2	62.4	133	70.5	0.4	0.53	0.85	0.45
	SBS	36,006	330.8	14.5	60.2	58.2	133	74.7	0.4	0.56	0.81	0.45
	MTBS	33,651	329.1	25.3	44.3	63.4	133	69.6	0.4	0.52	0.64	0.33
Graves Mountain (Kettle)	SBS	3,462	40.1	22	32.6	88.3	143	54.7	3.57	0.38	0.6	0.23
	MTBS	3,464	40.1	22	32.9	88	143	55	3.57	0.38	0.6	0.23
Lime Belt	FL	53,625	452.8	76.1	97.9	75.9	249.8	173.9	0.55	0.7	0.56	0.39
	SBS	54,000	420.6	78.4	98.2	73.3	249.8	176.5	0.59	0.71	0.56	0.39
	MTBS	55,482	324.9	86.3	95.2	68.3	249.8	181.5	0.77	0.73	0.52	0.38
North Star	FL	85,741	344.2	35.2	67.2	148	250.4	102.4	0.73	0.41	0.66	0.27
	MTBS	88,443	270.7	38.2	69.4	142.7	250.4	107.7	0.92	0.43	0.64	0.28
Renner (Kettle)	SBS	5,574	42.6	20.6	28.8	55	104.4	49.4	2.45	0.47	0.58	0.28
	MTBS	5,656	44.8	20.8	29.9	53.7	104.4	50.7	2.33	0.49	0.59	0.29
Stickpin (Kettle)	SBS	21,739	143.8	43.1	68.5	231.9	343.5	111.6	2.39	0.32	0.61	0.2
	MTBS	21,901	134.5	49.5	59.8	234.2	343.5	109.2	2.55	0.32	0.55	0.17
Tunk Block	FL	65,765	417.5	35.9	93.7	57.2	186.8	129.6	0.45	0.69	0.72	0.5
	MTBS	72,888	244	102.9	39.4	44.5	186.8	142.3	0.77	0.76	0.28	0.21
Twisp River	FL	4,538	41.8	4.4	3.9	1.9	10.2	8.3	0.24	0.82	0.47	0.38
	SBS	4541	42	4.4	3.9	1.9	10.2	8.3	0.24	0.82	0.47	0.38
	MTBS	4,558	39.6	4.5	3.8	1.9	10.2	8.3	0.26	0.82	0.46	0.38
2015 Wolverine Complex	FL	29,628	491.2	4.1	34.5	151.1	189.7	38.6	0.39	0.2	0.89	0.18
	SBS	26,437	427.9	0.2	5.9	183.6	189.7	6.1	0.44	0.03	0.97	0.03
	MTBS	26,843	361.5	5.3	0.9	183.5	189.7	6.2	0.52	0.03	0.14	0
2017 Wildfires												
Diamond Creek	FL	13018.3	183.9	0	1.3	63.6	64.9	1.3	0.35	0.02	1	0.02
	SBS	37755.7	634.4	0	1.3	63.6	64.9	1.3	0.1	0.02	1	0.02
	MTBS	36809.5	423.8	0	0.6	64.3	64.9	0.6	0.15	0.01	1	0.01
Uno Peak	FL	3500.91	109.8	0.9	2.7	113.3	117	3.6	1.07	0.03	0.74	0.02
	SBS	3463.83	120.9	1	2.6	113.4	117	3.6	0.97	0.03	0.73	0.02
	MTBS	3592.9	77.5	0.8	2.6	113.6	117	3.4	1.51	0.03	0.76	0.02

Table 7: Summary metrics of wildfire area and perimeter, total fireline length, length and percentage of engaged and held firelines, and the four calculated fireline metrics. Total fireline length to fire perimeter ratio (Tr), Engaged fireline to total fireline ratio (Er), Held to engaged fireline ratio (HEr), and Held to Total fireline ratio (HTr).

	Area ha	**Perim* km**	**Total length km**	**Engaged length km**	**%**	**Held length km**	**%**	**Tr**	**Er**	**HEr**	**HTr**
					2014 Wildfires						
Carlton Complex	103.49	437.9	385.2	230.7	60%	153.4	66%	0.88	0.6	0.66	0.4
					2015 Wildfires						
9 Mile*	1.91	26.8	27.4	22.9	84%	21.8	95%	1.02	0.83	0.95	0.79
Chelan Complex	36.01	330.8	133	74.7	56%	60.2	81%	0.4	0.56	0.81	0.45
Graves Mtn	3.46	40.1	143	54.7	38%	32.6	60%	3.57	0.38	0.6	0.23
Lime Belt	54.0	420.6	249.8	176.5	71%	98.2	56%	0.59	0.71	0.56	0.39
North Star*	85.74	344.2	250.4	102.4	41%	67.2	66%	0.73	0.41	0.66	0.27
Renner	5.57	42.6	104.4	49.4	47%	28.8	58%	2.45	0.47	0.58	0.28
Stickpin	21.74	143.8	343.5	111.6	32%	68.5	61%	2.39	0.32	0.61	0.2
Tunk Block*	65.76	417.5	186.8	129.6	69%	93.7	72%	0.45	0.69	0.72	0.5
Twisp River	4.54	42	10.2	8.3	81%	3.9	47%	0.24	0.82	0.47	0.38
Wolverine Complex	26.44	427.9	189.7	6.1	3%	5.9	97%	0.44	0.03	0.97	0.03
					2017 Wildfires						
Diamond Creek*	377.6	183.9	64.9	1.3	2%	1.3	100%	0.35	0.02	1	0.02
Uno Peak	34.6	120.9	117	3.6	3%	2.6	72%	0.97	0.03	0.73	0.02

* Perimeters from fireline records are used for these fires because Soil Burn Severity was unavailable for 9Mile, North Star and Tunk Block or was inaccurate in the case of Diamond Creek.

Task 3: Evaluation of landscape fuel treatment strategies

The latest version of IFTDSS offers a user-friendly interface and operational fire behavior modeling to evaluate landscape fuel treatment strategies and their influence on predicted fire behavior across fire weather scenarios. For new users, the IFTDSS help system provides detailed instructions, but we also created a detailed, step-by-step instructions for how we created treatment scenarios, available on our project website. As part of our final webinar and presentation to the Confederated Tribes of the Colville, we plan to introduce our geospatial layer of potential treatment units for North Central Washington and ways to test scenarios within IFTDSS for local managers. Because this task was designed for local fire and fuels management, we opted to present results in English units that are still most commonly used in wildland fire operations.

Baseline burn probability differed markedly between the Methow Valley and Republic priority landscapes with much higher burn probabilities and conditional flame lengths in the Republic landscape. For this reason, we chose to demonstrate the Republic landscape here, which had much more distinct differences between scenarios. All treatment scenarios, including the 10% scenario, influence landscape burn probability. The NW wind direction we used as input for the fire weather scenarios clearly impacts outcomes with much higher burn probabilities to the west/NW of the treated landscape and lower burn probability in the interior of treatment networks. However, achieving low burn probability across most of the treatment area required >40% of the landscape to be treated. Model results can be found on our project website. Under extreme summer fire weather, most of the base Republic landscape has high conditional flame lengths that would require indirect firefighting measures. Conditional flame length predictions closely mirror burn probability surfaces with marked differences between even the base landscape and 10% fuel treatment scenario (**Figure 13**). However, for conditional flame lengths to be reduced to below 4ft (and support direct suppression), over 30% of the landscape is required for treatment.

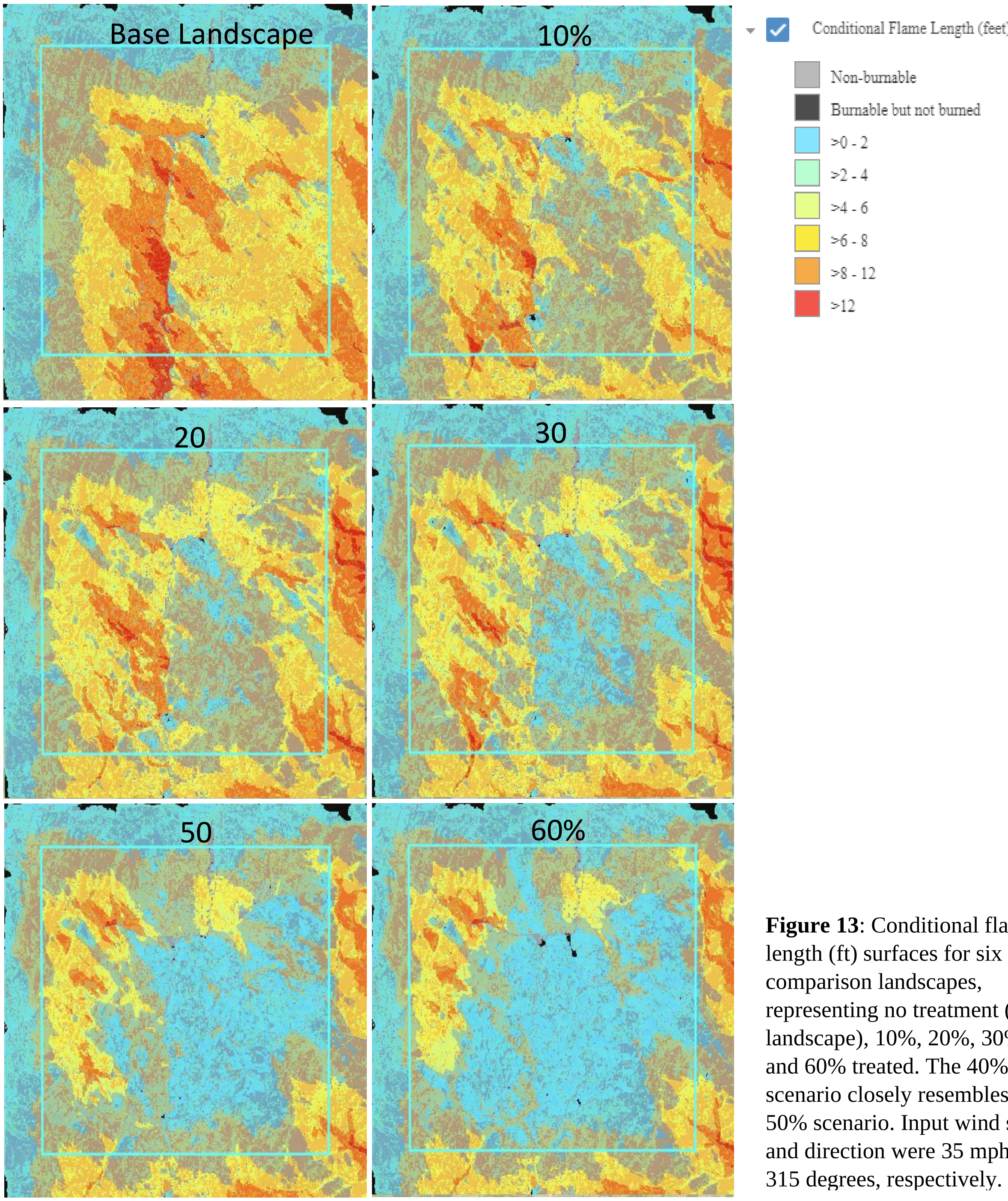

Figure 13: Conditional flame length (ft) surfaces for six comparison landscapes, representing no treatment (base landscape), 10%, 20%, 30%, 50%, and 60% treated. The 40% scenario closely resembles the 50% scenario. Input wind speed and direction were 35 mph and 315 degrees, respectively.

Science Delivery

To date, we have published the Carlton Complex analysis in *Ecological Applications* and contributed to a review of climate change adaptation to the Northwest Forest Plan that was just accepted by *Forest Ecology and Management*. We have presented findings at five conferences and as part of eight invited presentations. Next steps for science delivery include a final webinar to the Confederated Tribes of the Colville to present our methods and findings using IFTDSS to evaluate fuel treatment strategies and a final project webinar with the Northwest Fire Science Consortium. We are planning to schedule both for winter 2021-2022.

Table 8: Science delivery contributions, including date and a brief description.

Deliverable	Date	Description
Scientific manuscript #1	August 2020	Prichard, S.J., Povak, N., Kennedy, M.C., and Peterson, D.W. 2020. Fuel treatment effectiveness following the 2014 Carlton Complex Fire in semi-arid forests of north-central Washington State. Ecological Applications: e02104. https://doi.org/10.1002/eap.2104
Scientific manuscript #2	In press	Gaines, W., Hessburg, P., Aplet, G., Henson, P., Prichard, S., Churchill, D., Jones, G., Isaac, D.J., and Vynne, C. *In press*. Climate change and the Northwest Forest Plan: managing for dynamic landscapes. Forest Ecology and Management.
Scientific manuscript #3	In prep	Povak, N., Griffey, V., and Prichard, S.J. In prep. Landscape drivers of fire severity across multiple large wildfires in north-central Washington State. Ecosphere.
Scientific manuscript #4	In prep	Lemons, R., Prichard, S.J., and Kerns, R. In prep. Fireline effectiveness across large wildfire events in north-central Washington State. International Journal of Wildland Fire.
Conference and invited talks		
Association of Fire Ecology Conference	December 2021	Lemons, R., Prichard, S., and Kerns, B. Evaluating a method of fire line effectiveness in recent wildfires of north-central Washington State.
University of California Fire Science Seminar Series	October 2020	Prichard, S.J. Fuel Treatments and Megafires: lessons from the large fires in north-central WA
Washington on Fire Seminar Series, WSU Grad. and Prof. Student Science Policy Initiative	October 2020	Prichard, S. Why are wildfires increasing in the Pacific Northwest
California Forest Management Task Force Sierra and Eastside Regional Prioritization Group	July 2020	Prichard, S. Fuel Treatments and Megafires: lessons from the 2014 Carlton Complex, north-central WA
Fraser Basin Council (BC) Wildfire and Climate Change Webinar Series.	May 2019	Prichard, S. Effectiveness of fuel treatment in mitigating wildfire severity – lessons from large wildfire events in the interior Pacific Northwest
International Association of Landscape Ecology Conference (Fort Collins, CO)	April 2019	Kennedy, M. and Prichard, S. Incorporating spatial autocorrelation into fire severity modeling: implications for wildland fire management.
Colorado State University, Fort Collins, CO	April 2019	Prichard, S. Wildfires as a fuel treatment – lessons from recent large wildfires in the western US.
International Association for Landscape Ecology Conference, Fort Collins, CO.	April 2019	Prichard, S.J., Hessburg, P., Salter, R.B., Povak, N., and Gray, R.W. Wildfires as fuel reduction treatments: implications for landscape resilience.

Deliverable	Date	Description
UW College of the Environment Seminar	March 2018	Prichard, S.J. Western Wildfires: changing landscapes of the interior PNW
IAWF/AFE Fire Continuum Conference, Missoula, MT.	May 2018	Prichard, S.J., Peterson, D.W., Salter, R.B. and Povak, N. Retrospective analysis of fuel treatment effectiveness in the Carlton Complex fires, north-central WA
2nd Annual Cohesive Wildland Fire Management Strategy Workshop. Reno, NV.	March 2018	Prichard, S.J. Lessons learned from large wildfires: landscape fuel treatments and wildland fire management strategies
JFSP Final Report	October 2021	Final report to the Joint Fire Science Program
NW Science Webinar	Winter 2021	Webinar to present project findings, coordinated by the Northwest Fire Science Consortium

Conclusions

The National Cohesive Wildland Fire Management Strategy (Cohesive Strategy) calls for an all hands-all lands approach to foster more resilient landscapes and communities across the United States (Stratton 2020). As rapid climate change brings longer, hotter and often drier wildfire seasons to the western US, the imperative to increase the pace and scale of treatment grows. As with many regions of the western US, north-central Washington has experienced a steep rise in the incidence, size and severity of wildfires (Project StoryMap). Although trends in fire severity are not always toward greater stand replacement (Doerr and Santin 2016), recent summer wildfires in north-central Washington State have been dominated by large, severe events, creating large patches of stand replacement during large fire growth days (Cansler and McKenzie 2014, Reilly et al. 2017). Lessons learned about the effectiveness of fuel reduction treatments both in wildfire outcomes and assisting in wildfire response are therefore highly relevant to many fire-prone areas throughout the western United States.

In this study, we evaluated large wildfires that occurred during the record-setting 2014/2015 wildfire seasons in north-central Washington State. Our goal was to go beyond the classic evaluation of individual large wildfire events and focus on a set of regional fires that impacted both the forests and communities of our region. During a multi-year drought, the 2014/2015 wildfires burned nearly 400,000 ha in total, of which 212,000 ha were forested. Based on burned area reflectance classifications from pre- and post-burn satellite imagery, 25% of forested area within wildfire perimeters burned at high severity and 37% burned at moderate severity. From field-based calibrations between tree mortality and remotely sensed imagery, high tree mortality occurred in much of the area that burned at moderate and high severity (Prichard et al. 2014, 2020). Warmer and drier summers, combined with large patches of stand replacing wildfires, can pose challenges to tree regeneration. In drier sites, stand-replacing wildfires are increasingly associated with post-fire tree regeneration failure or delays and vegetation type change from forest to shrub steppe or grassland (Stevens-Rumann and Morgan 2019, Coop et al. 2020).

By evaluating a set of region-wide wildfires, we sought to better understand how the location and configuration of treatments can influence fire behavior and severity. These wildfires severely impacted local communities through major losses in structures (over 300 in the 2014 Carlton Complex alone), loss of commercial timberlands for the Confederated Tribes of the Colville, and major smoke impacts (Jaffe et al. 2020). Lessons learned on how past fuel reduction treatments assisted wildfire response and helped to corral fire spread and/or mitigate fire severity are essential to document so that communities in north-central Washington and other fire-prone regions can better prepare for future wildfire events, which are becoming increasingly inevitable under climate change. An important tool for developing and evaluating future fuel treatments is the Interagency Fuel Treatment Decision Support System. As part of this project, we developed a geospatial layer that allows decision makers to design potential fuel treatment layers for landscape burn probability evaluation.

Key Findings

***Task 1**: What were the main drivers of fire severity in large wildfire events of north-central Washington and how was fuel treatment effectiveness influenced by fire weather, biophysical environment, and topography?*

In this task, we evaluated how the location and configuration of treatments can influence fire behavior and severity in the context of fire weather, topography and other factors. We started with the 2014 Carlton Complex and then expanded the study area to include all large wildfires in north-central Washington State. We compared two approaches to spatial fire severity modeling, including SAR and RF modeling. We found both approaches to be highly complementary. Because the SAR models used the entire datasets within our N and S study areas, we were able to validate model inferences from RF modeling, which required subsampling of pixels to increase independence between sample points.

In the Carlton and region-wide analyses, fuel reduction treatments occupied a small portion of the total study area but were still significant factors in mitigating fire severity, even during extreme fire weather events. As other studies have found (Kalies and Kent 2016, Prichard et al. 2021), recent burns, either prescribed burns or past wildfires, were related to lower subsequent fire severity. Compared with first-entry fires, reburned areas exhibited a greater influence from bottom-up factors including topography, fuels, and past wildfire burn patterns compared to top-down drivers such as climate and fire weather. Maximum wind speed and direction were strongly correlated with higher fire severity, particularly for first-entry fires.

Biophysical setting was also a strong driver of fire severity. Study fires burned across large environmental gradients and models showed a general trend of higher severities in cooler and less arid climatic settings with higher fuel moistures, typical of higher elevation mixed conifer forests in the region. Given that weather and vegetation conditions can vary widely across a given fire -- particularly those that burn for multiple weeks and months -- we also assessed drivers of severity within the 10 largest progression intervals separately to better understand what drove severity under the most extreme conditions. The relative importance and direction of drivers varied more across burn days than across fires, indicating some variability in the dominant drivers even under the most severe burn periods. Furthermore, bottom-up drivers were still influential, suggesting that large spread days are not only driven by top-down factors alone.

These findings underscore how each fire spread event has a unique set of factors that drive fire behavior and severity. As such, building predictive models of fire severity for future fires will be difficult given the complexity and non-stationarity of the relationships within and among top-down and bottom-up factors. However, modern machine learning algorithms have the capacity to diagnose specific drivers of fire severity at a given point on the landscape (local variable importance) giving tremendous power to retrospective analyses to describe quantitatively the conditions under which past treatment, including fuel reduction treatments and past wildfires, played a role in mitigating fire severity under extreme weather. To this end we mapped local variable importance for variable groups (i.e., weather, topography, fuels, treatments) across fires and identified patterns in the relative influence of each in determining local fire severity.

***Task 2a**: How were past fuel treatments used in safe and effective response?*

Early in our project, we held in-person site visits with local fire managers from the Confederated Tribes of the Colville, Okanogan Wenatchee NF, Tonasket Ranger District, Colville NF, WDFW, and WA DNR. We compiled lessons learned about how fuel treatments were used to provide safe and effective firefighting response to the 2014/2015 wildfires (see project website). Some networks of fuel treatments were actively used to corral wildfires. Specifically, a large (8918 ha) unburned island within the 2014 Carlton Complex was actively defended by firefighting crews after the main passage of the north and south progressions of the fires. A network of large fuel reduction treatments, including the 2001 Leecher Mtn underburn, slowed fire spread as the northern flank backed down toward Benson Creek. As weather conditions became more favorable for direct attack, the large network of fuel treatments provided defensible space for firefighters to contain the wildfires and spare the unburned island. Similarly, units near Aeneas Valley along the northern portion of the 2015 North Star fire were used by local firefighters from the Tonasket Ranger District to conduct low-intensity burnout operations in advance of the wildfires. The network of fuel treatments and maintained roads were credited for corralling the wildfire away from Aeneas Valley. Even with these promising examples, and others highlighted in this report, local fire and fuels managers consistently spoke of how fuel reduction projects are not being conducted at the scale needed to prepare North Central Washington for future wildfire events.

Task 2b: *How did firelines perform in the 2014/2015 wildfire seasons, and what are best methods for calculating metrics of fireline effectiveness?*
Through a systematic review of fireline and perimeter source data, we first evaluated a method proposed by Gannon et al. (2020) to calculate metrics of fireline effectiveness. Based on comparison with uncorrected source data, we concluded that careful evaluation of source data perimeters and fireline classifications is warranted. However, because a 60-m buffer was used around actual firelines, correcting digitizing errors did not substantially change fireline length estimates or calculated metrics. Because MTBS dissolved unburned perimeters within supported perimeter files, we opted to use Soil Burn Severity perimeters, where available, as the most accurate source of perimeter data.

Overall, a total of 2205 km of fireline was evaluated in this analysis, of which 71% was bulldozer line (either as new dozer line or bulldozed old roads), 21% was existing road used as completed line, and 8% was hand line. Not counting road as completed lines, at total of 1742 km of new lines were constructed in these wildfires. Although the redigitizing work to correct fireline layers was not necessary for metric estimation, but this step may be important if reliable geospatial layers of firelines are needed for long-term post-fire rehabilitation and monitoring. Because fireline construction is expensive and can be associated with high post-fire rehabilitation costs and hydrological and ecological impacts, it is important to be able to evaluate their relative effectiveness. The four metrics proposed by Gannon et al. (2020) offer ways to summarize how much investment was made in fireline construction, how much fireline was engaged in the fire (i.e., burned over or held) and of engaged line, how much held. An overall ratio of the length of held line to the total fireline constructed is then provided to give an overall assessment of fireline effectiveness, considering how much actually engaged and was held by the fire.

Although the actual length of constructed fireline was quite high, relative to the large fire perimeters, most of the study area wildfires still fell within a low overall category of suppression (**Figure 11**, Tr < 1.0). However, some wildfires were notable exceptions including wildfires in which fire lines were constructed far from actual fire perimeters, as in the case of the 2015 Kettle Complex and Wolverine Complex fires and 2017 Diamond Creek fire. Remote firelines were not actually engaged by the wildfires, suggesting an extremely low return on investment with potentially high ecological impacts. For example, where firelines were newly constructed dozer lines, they are also associated with impacts from forest clearing and disturbed soil. Not surprisingly, higher fireline effectiveness was associated with areas that burned at lower severity and also within wildfires that had greater proportions of nonforest, both of which can substantially improve the chances that firelines remain barriers to spread.

Task 3*: Can strategic configurations of fuel treatments across fire-prone forested landscapes be effective at reducing future burn probability and predicted flame lengths?*
Our original objective for this task was to create our own web-based decision support tool to be used by local area managers. However, the recent version of IFTDSS offers a powerful set of modeling tools to guide landscape fuel treatment prescriptions. In our final task, we developed a fuel treatment planning layer based on common forest types, topography and aspect classes that can be used by managers in north-central Washington State for strategic planning purposes within IFTDSS. For demonstration purposes, we developed a range of fuel treatment scenarios that can guide future implementation of the Cohesive Strategy. We focused on two priority landscapes identified within the 20-year Forest Health

Strategic Plan for eastern Washington State, including Methow Valley and Republic. Because our study areas are dominated by low elevation mixed conifer forests, we applied a consistent fuel reduction treatment (i.e., forest thinning followed by a combination of pile burning and underburning) to randomly selected treatment units across scenario landscapes, ranging in treatment coverage from 10 to 60%.

To evaluate landscape thresholds to treatment effectiveness, we used the IFTDSS Landscape Burn Probability module to simulate a mid-summer wildfire with high (15 mph) to extreme (35 mph) winds from the NW. Across all treatment intensities (10 to 60%), fuel treatments reduced burn probability and conditional flame lengths. The lowest treatment scenario lowered burn probability downwind of the network of treatments, whereas treatment intensities > 40% effectively reduced burn probably to low across the treated area and reduced conditional flame lengths to below 4 ft, the threshold that allows for direct suppression techniques. The new version of IFTDSS makes running fire simulations very straightforward, but we decided that it would be helpful to provide step-by-step instructions for fire and fuels managers to follow. These are available on our project website.

Implications for Management/Policy

1) *Creating resilient landscapes to mitigate future fire severity and patch sizes of high severity fire events*

With projected warmer, drier and longer fire seasons, large wildfire events with extreme fire weather will become more common. Although there has been some understandable concern that extreme wildfire events, including some of the largest wildfires in our study area, would exceed treatment thresholds and render them ineffective, that is not what we found. Even in wind-driven fire progression days, local, bottom-up controls, including past fuel reduction treatments, mitigated fire severity. Wildland fire burns as a contagious process, and fire weather, associated with antecedent drought, high temperatures, low relative humidity and strong winds driving fire spread, reduces thresholds to burning. Our results suggest that thinning on its own can mitigate fire severity but is much less effective during extreme fire weather. Past treatments that were thinned followed by underburning (ThinUB) were most effective at mitigating fire severity during these events, particularly on leeward slopes. Our findings also suggest that we need a better understanding of the strategic placement of treatments to maximize the likelihood of them remaining effective during extreme fire weather and behavior. These findings will be helpful to managers and policymakers looking to increase pace and quality of fuel treatments in order to create and maintain resilient landscapes.

Predictive fire severity models based on past fire dataset are unlikely to be useful for fire management officers on an incident. The amount of data required to train these models is too large and dependent on burn day variables to develop one on the spot, and models built using data from past fires may not capture the complexity associated with an active fire. However, with the use of local importance metrics, it is possible to identify commonalities among large wildfires to determine the types of treatments, landscape positions, and weather conditions that afford the highest likelihood of success. Past wildfires generally reduced fire severity across all fires, and this effect was greatest when fires occurred <10 years prior to a given fire. However, there was relatively little area covered by reburns in the study. There were many instances where previous fires acted as barriers to fire spread rather than affecting severity directly. Local importance revealed that fuel reduction treatments were effective at reducing fire severity in some portion of every fire, which is significant given that these were historically large fires in the region. This provides additional evidence that fuel reduction treatments can be effective at reducing fire severity.

2) *Landscape fuel treatment strategies to assist in future wildfire response*

The goal of many forest restoration projects is not to limit the occurrence and spread of wildfires but rather ameliorate wildfire outcomes for when fire inevitably returns (Prichard et al. in press). As part of this strategy, planning networks of fuel reduction treatments and contingency lines in advance of future wildfire seasons can provide for defensible space and allow firefighters to conduct burnout operations and corral wildfires around communities and values at risk. In this report, we highlighted several examples about how networks of past fuel treatments were used in safe and effective response. We also documented how local fire crews were able to conduct low-intensity burnout operations associated with post-fire effects that resemble prescribed burn units. However, our interviews with local area managers and the relatively few examples of where fuel treatment networks were used in firefighting responses underscored how the pace and scale of treatment is insufficient. Treatments were sometimes useful but were not at the spatial scale to change wildfire outcomes across forested landscapes within our study area.

3) Fireline effectiveness monitoring

The amount of ground disturbance associated with constructed firelines represents areas that are susceptible to post-fire erosion events and invasive species (Keeley 2006). Past studies have shown that firelines may increase the spread and density of invasive species (Moroney and Rundel 2013, Merriam et al. 2006). Invasive species management is already challenging in post-fire environments and under rapid climate change (Kerns et al. 2020). Heavy equipment can not only spread invasive seeds but also open mineral soil beds for expansion of invasives into post-fire landscapes. Having a reliable way to estimate and summarize fireline construction provides a means to compare suppression investments across wildfire events, their potential ecological impacts (Chambers et al. 2019, Kerns et al. 2020) and inform rehabilitation strategies. As a retrospective analysis, the Gannon et al. (2020) method also could be used for planning and placement of future firelines to reduce costs and site impacts.

One of the remaining challenges for fireline effectiveness monitoring is the quality of record keeping by wildland fire managers. Quality standards would greatly improve the accuracy of final firelines and fire perimeters. With new advanced GPS units, it would be faster, easier, and accurate if all fireline crews carried a GPS to mark the fireline as they are created. In addition, completed lines should be properly attributed with a fireline type (e.g., newly constructed dozer line, reopened road, or existing road as completed line) along with a creation date. Standards in final fireline perimeters would also improve the consistency of the Gannon metrics. We concluded that Soil Burn Severity was likely the most accurate source for fireline perimeters, but these datasets are not available for all wildfires.

Future Research

Fire severity research: Although much has been learned about the type and duration of fuel treatment effectiveness, less is known about how to strategically place treatments on landscapes and how they may interact with fires during large fire growth days. For example, fuel treatments were generally more effective on leeward slopes in our study, which may suggest a strategy for increasing overall landscape resilience to future wildfire events. Wind modeling can be used to develop probability grids of wind speed and direction to help strategically allocate fuel treatments on topographic positions that may be protected from severe winds. These data could then be used to determine where fuel treatments might be strategically placed to help slow fire spread and mitigate wildfire severity. Such information can also be used in larger planning efforts to optimize the value of treatments across landscapes or larger planning areas.

To better understand drivers of fire severity, more research is required to elucidate the specific fire weather and climate conditions above which bottom-up controls become ineffective at mitigating fire severity. Many global fire severity modeling approaches favor a top-down approach, which may over-emphasize large scale predictors over local predictors. Further research using local importance RF modeling can evaluate local drivers of fire severity and how they vary spatially. With the large number of recent wildfires in the western US, fire severity modeling could be extended to other fires to include different climates, forest types, ownerships, and disturbance histories. Meta-analyses would be a useful approach to determine statistical similarity (e.g., ordination) among fires using their local importance values and help to identify clusters where fires exhibited similar fire behavior across drivers.

Firefighting effectiveness and use of past fuel treatments: Fuel treatments were used in specific cases to assist in safe and effective response to the 2014/2015 wildfires, but the examples we were able to highlight are still anecdotal and are not sufficient to support a quantitative analysis. Future work on this area of research is needed and would be greatly assisted if firefighting crews maintained daily incident records, including well-attributed geospatial records of burnout operations, fireline construction, and after-action reports of how fuel treatments were used. Some agencies, including the Washington DNR, are starting to make use of past fuel treatment records in addition to past wildfires to guide firefighting strategies. Better coordination of geospatial records before and during wildland fire events would enable researchers to fully investigate how treatments can be used for safe and effective response.

The fireline metrics introduced by Gannon et al. (2020) offer a consistent way to evaluate the effectiveness of constructed firelines. Future research could be conducted to better understand why firelines are more effective in certain wildfire events than others. Improved record keeping, including proper attribution of fireline type and construction date, would greatly assist with questions about when and where firelines were effective as either containment lines during mop-up operations or in active wildfire spread events. Post-fire studies including the impacts of firelines on site hydrology, soil erosion and invasive species are needed to better understand the ecological impacts of constructed firelines. Because invasive species are an important concern in post-fire environments, a better understanding of how equipment vs. exposure of mineral soil leads to invasive species issues would be helpful to guide direct firefighting strategies and minimize issues for post-fire rehabilitation and restoration.

Literature Cited

Abatzoglou, J. 2013. Development of gridded surface meteorological data for ecological applications and modelling. International Journal of Climatology 33(1): 121-131.

Beers, T.W., Dress, P.E, and Wensel, L.C. 1966. Aspect transformation in site productivity research.

Bessie W.C. and Johnson E.A. 1995. The relative importance of fuels and weather on fire behavior in subalpine forests. Ecology 76: 747–762

Bivand, R. and Piras. G. 2015. Comparing implementations of estimation methods for spatial econometrics. Journal of Statistical Software 63: 1–36.

Borcard, D. and Legendre, P. 2002. All-scale spatial analysis of ecological data by means of principal coordinates of neighbor matrices. Ecological Modelling 153: 51–68.

Breiman, L. 2001. Random forests. Machine Learning 45: 5–32.

Calkin, D.E., Thompson, M.P., and Finney, M.A. 2015. Negative consequences of positive feedbacks in US wildfire management. Forest Ecosystems 2: 9.

Cansler, C. A. and McKenzie, D. 2014. Climate, fire size, and biophysical setting control fire severity and spatial pattern in the northern Cascade Range, USA. Ecological Applications 24: 1037–1056.

Cansler, C.A., Kane, V.R., Hessburg, P.F., Kane, J.T., Jeronimo, S.M.A., Lutz, J., Povak, N.A., Churchill, D.J., and Larson, A.J. *In press*. Previous wildfires and management treatments moderate subsequent fire severity, but daily fire weather and annual climate anomalies are still important. Forest Ecology and Management.

Chambers, J.C., Brooks, M.L., Germino, M.J., Maestas, J.D., Board, D.I., Jones, M.O., and Alfred, B.W. 2019. Operationalizing resilience and resistance concepts to address invasive grass-fire cycles. Frontiers in Ecology and Evolution 185(7): 1-25.

Coop, J.D., Parks, S.A., Stevens-Rumann, C.S., Crausbay, S.D., Higuera, P.E., Hurteau, M.D., Tepley, A., Whitman, E., Assal, T., Collins, B.M., Davis, K., Dobrowski, S., Falk, D.A., Fornwalt, P.J., Fulé, P.Z., Harvey, B.J., Kane, V.R., Littlefield, C.E., Margolis, E.Q., North, M., Parisien, M., Prichard, S., and Rodman, K.C. 2020. Wildfire-driven forest conversion in western North American landscapes. BioScience 70: 659–673.

De'ath, G. and Fabricius, K.E. 2000. Classification and regression trees: a powerful yet simple technique for ecological data analysis. Ecology 81: 3178–3192.

Dillon, G.K., Holden, Z.A., Morgan, P., Crimmins, M.A., Heyerdahl, E.K. and Luce, C.H. 2011. Both topography and climate affected forest and woodland burn severity in two regions of the western US, 1984 to 2006. Ecosphere 2(12): 1-33.

Doerr, S.H. and Santin, C. 2016. Global trends in wildfire and its impacts: perceptions versus realities in a changing world. Philosophical Transaction of the Royal Society B 371: 20150345.

Eidenshink, Schwind, B., Brewer, K., and Zhu, Z. 2007. A project for monitoring trends in burn severity. Fire Ecology 3(1): 3-21.

Gannon, B.M., Thompson, M.P., Deming, K.Z., Bayham, J., Wei, Y. and O'Connor, C.D. 2020. A geospatial framework to assess fireline effectiveness for large wildfires in the western US. Fire 3: 43.

Gebert, K.M., Calkin, D.E., and Yoder, J. 2007. Estimating suppression expenditures for individual large wildland fires. Western Journal of Applied Forestry 22(3): 188-196.

Goulden, M.L. and Bales, R.C. 2019. California forest die-off linked to multi-year deep soil drying in 2012–2015 drought. Nature Geoscience 12(8): 632-637.

Hessburg, P.F., Churchill, D.J., Larson, A.J. et al. 2015. Restoring fire-prone Inland Pacific landscapes: Seven core principles. Landscape Ecology 30: 1805–1835.

Hessburg, P.F., Miller, C.L., Parks, S.A., Povak, N.A., Taylor, A.H., Higuera, P.E., Prichard, S.J., North, M.P., Collins, B.M., Hurteau, M.D. and Larson, A.J., 2019. Climate, environment, and disturbance history govern resilience of western North American forests. Frontiers in Ecology and Evolution 7: 239.

Ishwaran, H. and Kogalur, U.B. 2018. Random forests for survival, regression, and classification (RF-SRC), R package version 2.6.1. https://www.rdocumentation.org/packages/ randomForestSRC/versions/2.9.3/topics/randomForestSRCpackage

Jaffe, D.A., O'Neill, S.M., Larkin, N.K., Holder, A., Peterson, D.L., Halofsky, J.E., and Rappold, A.G. 2020. Journal of the Air and Waste Management Association 70(6): 583-615.

Kalies, E. L. and Yocom Kent, L. 2016. Tamm Review: Are fuel treatments effective at achieving ecological and social objectives? A systematic review. Forest Ecology and Management 375: 84–95.

Kane, V.R., Cansler, C.A., Povak, N.A., Kane, J.T., McGaughey, R.J., Lutz, J.A., Churchill, D.J. and North, M.P. 2015. Mixed severity fire effects within the Rim fire: Relative importance of local climate, fire weather, topography, and forest structure. Forest Ecology and Management 358: 62-79.

Kennedy, M.C. and Prichard, S.J. 2017. Choose your neighborhood wisely: implications of subsampling and autocorrelation structure in simultaneous autoregression models for landscape ecology. Landscape Ecology 32: 945–952.

Kerns, R., Tortorelli, C., Day, M.A., Nietupski, T., Barros, A.M.G., Kim, J.B. and Krawchuk, M.A. 2020. Invasive grasses: a new perfect storm for forested ecosystems? Forest Ecology and Management 463: 117985.

Keeley, J.E. 2006. Fire management impacts on invasive plants in the western United States. Conservation Biology 20(2): 375-384.

Komisarczyk, K., Kozminski, P., Maksymiuk, S. and Biecek, P. 2021. treeshap: Fast SHAP values computation for ensemble models. R package version 0.0.1. https://github.com/ModelOriented/treeshap

LANDFIRE. 2012. Canopy base height and Existing Vegetation Type layers (LF 1.3.0). Landfire.gov

Lydersen, J.M., Collins, B.M., Brooks, M.L., Matchett, J.R., Shive, K.L., Povak, N.A., Kane, V.R. and Smith, D.F., 2017. Evidence of fuels management and fire weather influencing fire severity in an extreme fire event. Ecological Applications 27(7): 2013-2030.

Merriam, K., Kelley, J., and Beyers, J. 2006. Fuel breaks affect nonnative species abundance in California Plant Communities. Ecological Applications 16(2): 515-527.

Mornoney, J. and Rundel. P. 2013. Effects of fire and fireline disturbance on the plant community in a southern California ecological reserve. Madroño. 60(3): 173-178.

Parks, S.A. and Abatzoglou, J.T. 2020. Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985-2017. Geophysical Research Letters: e2020GL089858.

Parks, S.A., Dillon, G.K., and Miller, C. 2014a. A new metric for quantifying burn severity: the relavitized burn ratio. Remote Sensing 6: 1827-1844.

Parks, S.A., Holsinger, L.M., Panunto, M.H., Jolly, W.M., Dobrowski, S.Z. and Dillon, G.K. 2018a. High-severity fire: evaluating its key drivers and mapping its probability across western US forests. Environmental Research Letters 13(4): 044037.

Parks, S.A., Holsinger, L.M., Voss, M.A., Loehman, R.A. and Robinson, N.P. 2018b. Mean composite fire severity metrics computed with Google Earth Engine offer improved accuracy and expanded mapping potential. Remote Sensing 10(6): 879.

Parks, S.A., Miller, C., Nelson, C.R. and Holden, Z.A. 2014b. Previous fires moderate burn severity of subsequent wildland fires in two large western US wilderness areas. Ecosystems, 17(1): 29-42.

Parsons, A., Robichaud, P.R., Lewis, S.A., Napper, C., and Clark, J.T. 2010. Field guide for mapping post-fire soil burn severity. RMRS-GTR-243. US Forest Service Rocky Mountain Research Station, Fort Collins, CO. 49 p.

Povak, N.A., Kane, V.R., Collins, B.M., Lydersen, J. and Kane, J. 2020. Multi-scaled drivers of severity patterns across land ownerships for the 2013 Rim Fire, California. Landscape Ecology 35(2): 293-318.

Prichard, S.J., Hessburg, P.F., Hagmann, R.K., Dobrowski, S., Povak, N.A., Hurteau, M.D., Kane, V.R., Keane, R.E., Kobziar, L.N., Kolden, C.A., North, M., Parks, S.A., Safford, H.D., Stevens, J.T., Yocom, L.L., Churchill, D.J., Gray, R.W., Huffman, D.W., Lake, F.K. and Khatri-Chhetri, P. 2021. Adapting western North American forests to climate change and wildfires: ten common questions. Invited feature. Ecological Applications: e02433.

Prichard, S.J. and Kennedy, M.C. 2014. Predicting fire severity following an extreme wildfire event: effects of fuel treatment, landform, and weather. Ecological Applications 24:571-590.

Prichard, S.J., Povak, N., Kennedy, M.C., and Peterson, D.W. 2020. Fuel treatment effectiveness following the 2014 Carlton Complex Fire in semi-arid forests of north-central Washington State. Ecological Applications: e02104.

Reilly, M.J., Dunn, C.J., Meigs, G.W., Spies, T.A., Kennedy, R.E., Bailey, J.D. and Briggs, K. 2017. Contemporary patterns of fire extent and severity in forests of the Pacific Northwest, USA (1985-2010). Ecosphere 8: e01695.

Rothermel, R.C. 1983. How to predict the spread and intensity of forest and range fires. INT-GTR-143. US Forest Service Intermountain Forest and Range Experiment Station, Logan, UT. 161 p.

Schoennagel, T., Veblen, T.T. and Romme, W.H. 2004. The interaction of fire, fuels, and climate across Rocky Mountain forests. BioScience 54(7): 661-676.

Scott, J. and Burgan, R.E. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. RMRS-GTR-153. US Forest Service, Rocky Mountain Research Station, Fort Collins, CO. 172 p.

Stephens, S.L., McIver, J.D., Boerner, R.E.J., Fettig, C.J., Fontaine, J.B., Hartsough, B.R., Kennedy, P.L. and Schwilk, D.W. 2012. The effects of forest fuel-reduction treatments in the United States. BioScience 62: 549–560

Stratton, R.D. 2020. The path to strategic wildland fire management planning. Wildfire 29(1): 24-31.

Stevens Rumann, C.S. and Morgan, P. 2019. Tree regeneration following wildfires in the western US: a review. Fire Ecology 15:1-17.

Turner, M.G. and Romme W.H. 1994. Landscape dynamics in crown fire ecosystems. Landscape Ecology 9: 59-77.

Wright, M.N. and Ziegler, A. 2017. Ranger: A fast implementation of Random Forests for high dimensional data in C++ and R. Journal of Statistical Software 77(1): 1-17.

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Appendix B: Science Delivery

List of Completed/Planned Scientific/Technical Publications/Science Delivery Products: Identify scientific/technical publications that were produced during the project, to include:

Articles in peer-reviewed journals

The following articles are directly related to this JFSP project

Gaines, W., Hessburg, P., Aplet, G., Henson, P., Prichard, S., Churchill, D., Jones, G., Isaac, D.J., and Vynne, C. *In press*. Climate change and the Northwest Forest Plan: managing for dynamic landscapes. Forest Ecology and Management

Prichard, S.J., Povak, N., Kennedy, M.C., and Peterson, D.W. 2020. Fuel treatment effectiveness following the 2014 Carlton Complex Fire in semi-arid forests of north-central Washington State. Ecological Applications: e02104. https://doi.org/10.1002/eap.2104.

Funding from this project also contributed to our participation in the following review papers:

Hessburg, P.F., Prichard, S.J., Hagmann, R.K., Povak, N.A., and Lake, F.K. 2021. Wildfire and climate adaptation: is it needed in the western US? Invited feature. Ecological Applications.

Hagmann, R.K., Hessburg, P. F., Prichard, S.J., Povak, N. A., Brown, P.M.,, Fulé, P.Z., Keane, R. E., Knapp, E.E., Lydersen, J. M., Metlen, K. L., Reilly, M.J., Sánchez Meador, A.J. Stephens, S.L., Stevens, J. T., Taylor, A.H., Yocom, L.L., Battaglia, M.A., Churchill, D.J., Daniels, L.D., Falk, D. A., Henson, P., Johnston, J.D., Krawchuk, M.A., Levine, C.R., Meigs, G.W., Merschel, A.G., North, M. P., Safford, H.D., Swetnam, T.W., Waltz, A.E.M. 2021. Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. Invited feature. Ecological Applications.

Prichard, S.J., Hessburg, P.F., Hagmann, R.K., Dobrowski, S., Povak, N.A., Hurteau, M.D., Kane, V.R., Keane, R.E., Kobziar, L.N., Kolden, C.A., North, M., Parks, S.A., Safford, H.D., Stevens, J.T., Yocom, L.L., Churchill, D.J., Gray, R.W., Huffman, D.W., Lake, F.K. and Khatri-Chhetri, P. 2021. Adapting western North American forests to climate change and wildfires: ten common questions. Invited feature. Ecological Applications.

Coop, J.D., Parks, S.A., Stevens-Rumann, C.S., Crausbay, S., Higuera, P.E., Hurteau, M.D., Tepley, A., Whitman, E., Assal, T., Collins, B.M., Davis, K.T., Dobrowski, S., Falk, D.A., Fornwalt, P.J., Fulé, P.Z., Harvey, B.J., Kane, V.R., Littlefield, C.E., Margolis, E.Q., North, M., Parisien, M,-A., Prichard, S., and Rodman, K.C. 2020. Wildfire-driven forest conversion in western North American landscapes. BioScience. biaa061, https://doi.org/10.1093/biosci/biaa061

Planned peer-reviewed manuscripts

Lemons, R., Prichard, S. and Kerns, R. In prep. Evaluating a methodology for measuring fireline effectiveness. International Journal of Wildland Fire.

Povak, N., Prichard, S., Griffey, V., Salter, R.B., and Hessburg, P.F. In prep. Local importance of burn severity metrics in large wildfire events of the inland Pacific Northwest. Ecosphere.

Prichard, S.J., Salter, R. B., Povak, N., Gray, R.W., and Hessburg, P.F. in prep. Evaluating fuel treatment strategies within the Interagency Fuel Treatment Decision Support System. International Journal of Wildland Fire.

Conference presentations

Kennedy, M.C. and Prichard, S.J (copresenters). "Incorporating spatial autocorrelation into burn severity modeling: implications for wildland fire management." International Association of Landscape Ecology Conference, April 8, 2019. Fort Collins, CO.

Prichard, S.J. and Hessburg, P. WildLinks Conference: "Climate, environment, and disturbance history govern resilience of western North American forests" October 21, 2019. Cascadia Partner Forum, Vancouver, BC

Prichard, S.J., Hessburg, P., Salter, R.B., Povak, N., and Gray, R.W. "Wildfires as fuel reduction treatments: implications for landscape resilience." April 9, 2019. International Association for Landscape Ecology Conference, Fort Collins, CO.

Prichard, S.J., Peterson, D.W., Salter, R.B. and Povak, N. "Retrospective analysis of fuel treatment effectiveness in the Carlton Complex fires, north-central WA." May 21, 2018. IAWF/AFE Fire Continuum Conference, Missoula, MT.

Prichard, S.J. "Lessons learned from large wildfires: landscape fuel treatments and wildland fire management strategies." 2nd Annual Cohesive Wildland Fire Management Strategy Workshop. March 28, 2018. Reno, NV.

Workshops

Prichard, S., Hessburg, P., Hagmann, K. Wildfire in the West – Virtual Workshop (Institute for Journalism and Natural Resources). Western forests and wildfires: adapting western US forests to climate change and wildfires. April 22, 2021.

Prichard, S.J. Water's Vulnerability to Fire Workshop: "Fuel Reduction Treatments: lessons from east-side dry mixed conifer forests", November 5, 2018. Cedar River Watershed, North Bend, WA.

Prichard, S.J., Gray, R.W. December 2018. Project update meeting to the Confederated Tribes of the Colville.

Prichard, S.J., Gray, R.W. March 2021. Project update meeting to the Confederated Tribes of the Colville.

Webinars

Prichard, S. Cascadia Wildland and Urban Smoke Webinar Series. "Why are Wildfires Increasing in the PNW?" March 3, 2021. https://www.youtube.com/watch?v=_RTmcSHxt-8

Prichard, S. Washington on Fire Seminar for the Graduate and Professional Student Science Policy Initiative. October 20, 2020. https://www.youtube.com/watch?v=hKtqJrGwzEU

Prichard, S. University of California Fire Science Seminar Series. "Fuel Treatments and Megafires: lessons from the large fires in north-central WA" October 1, 2020.
https://www.youtube.com/watch?v=EYp33ojpW5g&list=PLvPofWzmi8889iiaMSPtzUD0VLqxyo-fz&index=5&t=23s

Prichard, S. California Forest Management Task Force Sierra and Eastside Regional Prioritization Group "Fuel Treatments and Megafires: lessons from the 2014 Carlton Complex, north-central WA" July 10, 2020.

Prichard, S. Association of Women in Science – Seattle Chapter. "Wildfires and Climate Change in the Pacific Northwest." December 16, 2020.

Prichard, S.J. Webinar: Wildfire and Climate Change Webinar Series. "Effectiveness of fuel treatment in mitigating wildfire severity – lessons from large wildfire events in the interior Pacific Northwest." May 16, 2019. Fraser Basin Council, BC. https://www.youtube.com/watch?v=sb14MwucyrY

Other invited presentations

Prichard, S.J. Invited lecture: "Wildfires as a fuel treatment – lessons from recent large wildfires in the western US." April 9, 2019. Colorado State University, Fort Collins, CO.

Prichard, S.J. Seminar: University of Idaho School of Natural Resource Seminar Series: "Wildfires as a fuel treatment - lessons from recent large wildfires in the western US." March 20, 2019. Moscow, Idaho.

Prichard, S.J. UW College of the Environment Seminar. “Western Wildfires: changing landscapes of the interior PNW.” March 6, 2018. University of Washington, Seattle, WA.

Project website

Our project website will be updated with the latest presentations and publications associated with this project: https://depts.washington.edu/nwfire/ncw/

StoryMap

An ArcGIS StoryMap was developed to display interactive time series maps of burned are and fire severity. We intend to continue to expand on this with assistance from the Washington Department of Natural Resources to communicate with stakeholders about the recent impacts of wildfires to north-central Washington and the need for adaptive management.
https://storymaps.arcgis.com/stories/da2c6d84fa67456c87d0c2f891f3e0cf

Appendix C: Metadata

We are closely following our project data management plan. Because we did not pursue interviews with incident management teams, there are no social science data associated with this project. Similarly, because we used the IFTDSS, which has built-in gridded wind and weather, we were also able to simplify the data required for wildland fire simulations. The three main data types associated with this project are:

1. Burn severity modeling inputs, including geospatial records of past fuel treatments, topographic variables, past wildfires, fire weather and burn severity indices,
2. Fireline datasets including original and corrected lines, wildland fire perimeters, and calculated effectiveness metrics.
3. A geospatial layer of potential fuel treatment patches along with treated landscape scenarios, ranging from 10% to 60% treated.

As specified in our data management plan, published datasets are being archived with the USFS Research Data Archive, and project metadata are prepared in the Biological Data Profile of the FGDC Content Standard for Digital Geospatial Metadata (FGDC-STD-001.1-1999). Metadata for geospatial datasets without a biological component are prepared in the FGDC Content Standard for Digital Geospatial Metadata (FGDC-STD-001-1998).

Research Data Archive (Carlton Analysis): https://www.fs.usda.gov/rds/archive/Catalog/RDS-2020-0003

We are using the Open Science Framework for project documentation and have three corresponding pages (called components) to document these datasets along with source scripts, metadata, publications and presentations. Data descriptions and sources are available for draft manuscripts, including the 2014/2015 global fire severity analysis (Povak et al. in prep) and the fireline effectiveness analysis (Lemons et al. in prep) are available on our North Central Wildfire Open Science Framework Page: https://osf.io/3nukg/