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Complete List of Authors:	Stevens-Rumann, Camille; University of Idaho, Prichard, Susan; University of Washington Strand, Eva; University of Idaho Morgan, Penelope; University of Idaho
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Prior wildfires influence burn severity of subsequent large fires

Camille S. Stevens-Rumann, Susan J. Prichard, Eva K. Strand, Penelope Morgan

C.S. Stevens-Rumann (Corresponding author), E.K. Strand, P. Morgan
University of Idaho
Department of Forest, Rangeland, and Fire Sciences
875 Perimeter Drive MS 1133
Moscow, ID 83844
Email: csrumann@uidaho.edu
Phone: 602-509-5077
Fax: 208-885-6564

S.J. Prichard
University of Washington
School of Environmental and Forest Sciences
University of Washington
Seattle, WA 98195-2100

Abstract

With longer and more severe fire seasons predicted, incidence and extent of fires is expected to increase in western North America. As more area is burned, past wildfires may influence the spread and burn severity of subsequent fires, with implications for ecosystem resilience and fire management. We examined how previous burn severity, topography, vegetation, and weather influenced burn severity on four wildfires, two in Idaho, one in Washington, and one in British Columbia. These were large fire events, together burning 330,000 ha and cost $165 million USD in fire suppression expenditures. Collectively, these four study fires reburned over 50,000 ha previously burned between 1984 and 2006. We used sequential autoregression to analyze how past fires, topography, vegetation, and weather influenced burn severity. We found that areas burned in the last three decades, at any severity, had significantly lower severity in the subsequent fire. Final models included maximum temperature, vegetation cover type, slope, and elevation as common predictors. Across all study fires and burning conditions within them, burn severity was reduced in previously burned areas, suggesting that burned landscapes mitigate subsequent fire effects even with the extreme fire weather under which these fires burned.

Key words: fire weather; reburn; repeated wildfires; sequential autoregression; self-regulation

Introduction

As a self-regulating process, the pattern of previous fires may limit the progression and burn severity of subsequent wildfires for some time due to limited burnable fuels and changes in forest structure (Agee 1999; Peterson 2002; Parks et al. 2014, 2015; Coop et al. 2016). Over the past century, the legacy of past land use changes and fire exclusion have influenced forest landscapes over much of the western United States (Hessburg et al. 2015). After nearly a century of fire exclusion, many dry forests of the western United States have altered stand structures and landscape patterns that can contribute to larger and more severe wildfire events (Hessburg et al. 2015; Parks et al. 2015). With the onset of warmer, drier summers and warm springs, the number and size of wildfires is increasing in the western US and other fire-prone ecosystems throughout the world (Littell et al. 2009; Jolly et al. 2015). Burn severity, defined as the magnitude of ecological effects of fires (Prichard and Kennedy 2014), has been less studied than area burned. With the growing number of large wildfires and costly wildfire seasons, a better understanding of fire on fire interactions and their implications for ecological effects is needed to inform science and management of fires.

Previous researchers have found that burn severity of wildfires was influenced by the burn severity of prior fire. To date, many of these studies were in large wilderness areas in which wildfires have had limited fire suppression and were managed and monitored (e.g. Collins et al. 2009; van Wagtendonk et al. 2012; Parks et al. 2014). In studies of past fire interactions in the Sierra Nevada Range, Collins et al. (2009) and van Wagtendonk et al. (2012) found that areas previously burned with low to moderate severity within the past 30-years tended to burn at similar severity in a subsequent fire. However, if an area had previously burned in a high severity fire, a high proportion of the area burned at high severity in a subsequent fire. They attributed this to the fire-induced shift in vegetation from forests to highly flammable shrublands rather than simply a function of post-fire fuel accumulation (van Wagtendonk et al. 2012). Similarly, Holden et al. (2010) found that in wildfires 3 to 14 years prior there was a threshold for burn severity above which burn severity is likely to increase in the subsequent fire. Based on inferences from satellite imagery combined with field data, low severity fires often resulted in subsequent low severity fires, but high severity fires resulted in subsequent high severity fires (Holden et al. 2010; Parks et al. 2014a). In this study we focus on non-wilderness areas. Fires outside of wilderness areas are often in drier forest types (Haire et al. 2013), tend to have the highest fire suppression costs, and these areas have high public interest and use.

Topography, vegetation, and fire weather influence burn severity of wildfires (Schoennagel et al. 2004; Lentile et al. 2007; Prichard and Kennedy 2014; Birch et al. 2015), but whether these variables supersede or compound the influence of prior fires is not well understood. Previous studies have reported mixed findings on the relative importance of top-down drivers of fire, such as maximum temperature, relative humidity, and wind speeds, and bottom-up drivers, such as vegetation and topography. Bessie and Johnson (1995) and Gedalof et al. (2005) demonstrated that extreme weather conditions can override bottom-up factors, resulting in larger wildfires regardless of fuels and forest types. In contrast, Birch et al. (2015) found that bottom-up factors, including vegetation and site potential, influenced burn severity more than climate and weather. Though multiple researchers have examined bottom-up versus top-down drivers of burn severity, few have analyzed the influence of these factors in previously burned areas over multiple large fires. Some research has found that wildfires burning under very hot, dry, and windy conditions are more likely to overcome fuel breaks even those created by previous wildfires (Pollet and Omi 2002). To better understand the capacity of burn mosaics to be self-regulating, we must understand when and why past wildfires alter subsequent burn severity and when environmental factors or day of burning conditions override the legacy effects of prior fires.

Here we focus on the legacy of previous wildfires by examining the drivers of burn severity within reburned areas in non-wilderness forests of the interior northwestern US. We studied the Tripod Complex Fire (central Washington, USA), the East Zone Complex (central Idaho, USA), Cascade Complex Fires (central Idaho, USA), and Kootenay Fire (central British Columbia, Canada); each of which were unusually large, severe, and expensive relative to those of the prior century, and each burned through areas burned by numerous past fires. We used sequential autoregression (SAR) analysis to evaluate the influence of past wildfires, weather and topography on burn severity. SAR has been used in recent studies of burn severity to take advantage of the inherent spatial autocorrelation in burn severity datasets (Wimberly et al. 2009, Prichard and Kennedy 2013). The effectiveness of fuels treatments, including prescribed fires, have been previously studied on two of these wildfires (Hudak et al. 2011; Prichard and Kennedy 2014), but neither included previous wildfires that may have also modified burn severity. Our study was guided by two key questions: (1) How was burn severity of subsequent wildfires influenced by previous wildfires? and (2) What role does weather, vegetation and topographic conditions have on burn severity? These questions are critical for forecasting the implications for future resilience and vulnerability, as well as understanding how post-fire fuel conditions will influence subsequent burn severity and when and where the legacy of these past burns can be used in wildfire management to achieve vegetation management or restoration goals. Additionally, we address how weather, topography, vegetation, and past wildfires to influence subsequent burn severity and how relationships differ between the four events.

Methods

Study areas

We focused our study on four recent, large wildfires in Idaho, Washington, and British Columbia (Figure 1). These wildfires were chosen due to their large size, high fire suppression costs, and large areas of interactions with previous wildfires. Combined, these four fire complexes burned a total of 330,000 ha and cost over $165.5 million USD in fire suppression (Filmon 2003; Hudak et al. 2011; Prichard and Kennedy 2015). Our four study fires occurred in years of widespread fires across their respective regions (Filmon 2003; Hudak et al. 2011). In three of the four cases these wildfires were complexes started from multiple ignitions that burned into one another and were managed as a single fire.

The 2006 Tripod Complex on the Okanogan-Wenatchee NF in Washington was, at the time, the largest (70,894 ha) fire event in Washington State and cost $82 million USD in fire suppression costs (Prichard and Kennedy 2014). Over 65% of the area burned at moderate to high burn severity with stand replacement. The wildfires in this complex ignited from lightning in high elevation forests of lodgepole pine (*Pinus contorta*) and Engelmann spruce (*Picea engelmannii)*. The wildfires then spread into surrounding mixed-conifer forests of Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine *(Pinus ponderosa*) and western larch (*Larix occidentalis*). As the Tripod Complex spread northeast with prevailing winds, it burned portions of three 2003 burns, three 2001 burns, and burned a small portion of one 1994 burn (Figure 2a).

The 2003 Kootenay Fire Complex (Kootenay National Park, British Columbia) was one of the largest fire events to have occurred in the Canadian Rockies in park history, burning 17,400 ha and costing $10.3 million USD for fire suppression. Over 75% of the area burned at moderate to high severity. Pre-fire fuel complexes were comprised of mature mixed-conifer forests of lodgepole pine, Engelmann spruce, and subalpine fir (*Abies lasiocarpa*). This wildfire was mostly stand replacing and burned into a wildfire from 2001 (Figure 2b). This fire occurred within a Canadian national park, but full suppression of all wildfires was the standard operating procedure before 2004, thus this fire and those points of interaction were similar to the national forest study areas within the US (Day et al. 1990).

In 2007, the East Zone and Cascade Complex fires each burned over 128,000 ha on the Boise and Payette National Forests in Idaho (Hudak et al. 2011) and cost \$32.5 and \$40.7 million USD respectively in fire suppression. The East Zone and Cascade Complexes burned with mixed burn severity, with 21 to 30% of each wildfire classified as high severity (Stevens-Rumann and Morgan *in press*). These two complexes burned through a wide range of forest types and elevations from subalpine forests and meadows at high elevation to lower tree line dominated by ponderosa pine woodlands. These two wildfires interacted with 31 previous wildfires that burned between 1984 and 2006 (Figure 2c). Although the 2007 Cascade and East Zone Complexes shared borders, we analyzed these fires separately given their large size and the computational resources required to analyze these large landscapes.

Datasets

We used data from multiple sources to examine drivers of burn severity (Table 1). We assessed the impact of previous wildfires by evaluating burn severity using a continuous Relative Differenced Normalized Burn Ratio (RdNBR; Miller et al. 2009) for the three US fires which was obtained from the Monitoring Trends in Burn Severity (MTBS) project (Eidenshink et al. 2007). We chose RdNBR over other metrics of burn severity because it is generally a reliable predictor of field-validated burn severity (Miller et al. 2009; Prichard and Kennedy 2014) and is especially suitable for heterogeneous vegetation (Parks et al. 2015). Additionally, field-based composite burn index (CBI) values on the Tripod Complex Fire were highly correlated with RdNBR ($R^2 = 0.71$; Prichard and Kennedy 2014). For the Kootenay Fire, we used Differenced Normalized Burn Ratio (dNBR) which was post-processed by Kootenay National Park. Due to the largely homogenous cover type on this fire dNBR was considered to be an appropriate proxy (Miller and Thode 2007).

We used the MTBS data for the prior fires for three potential predictor variables. First, we converted continuous RdNBR and dNBR values for past fires into categorical variables of "unchanged/unburned", "low", "moderate", and "high" using metric specific thresholds established by Miller and Thode (2007) to apply consistent classifications between study areas. For our analysis, categorical variables were required to have a base contrast for regression comparisons, thus we used unburned/unchanged as the base contrast. Second, time since fire was assigned for each pixel that experienced 2 or more fires since 1984. For pixels not previously burned we assigned "100" as time since previous fire. We categorized these as "100" years since fire because burn severity data inferred from Landsat satellite imagery is only available after 1984 and most of these forests are known to be dominated by 80-120 year old trees (Schellhaas et al. 2001). For pixels that were reburned more than once (i.e., burned in three or more wildfires between 1984 and 2007), the most recent fire year was used to calculate time since previous fire. This did not occur on the Kootenay Fire and occurred on two percent of the reburned area of the Tripod Fire. On the Cascade Complex Fire this occurred on three percent of reburned pixels and on the East Zone Complex Fires on four percent. Third, to understand possible edge effects, such as fire suppression and changes in fire behavior along a fires perimeter, we used a distance-to-edge metric calculated as the distance of each pixel to the nearest burn perimeter. Although fire management actions during wildfires likely altered fire extent and burn severity, we did not account for them directly as the records of management actions were incomplete.

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

To examine the impact of weather on the day of burning, we acquired fire progression interval layers from the Okanogan-Wenatchee, Boise, and Payette National Forests, and from Kootenay National Park. These progression layers allow us to narrow the time frame within which each pixel burned to a 10-96 hour window depending on the frequency progression intervals were sampled from infrared imagery. We then assigned weather characteristics during each progression interval based on the date each pixel burned. We assigned maximum and average wind taken at 6.1 m above ground, maximum and average air temperature, and minimum relative humidity (RH). These data were acquired from nearby Remote Area Weather Stations (RAWS): the First Butte station for the Tripod, the Tea Pot Idaho station for the Cascade and East Zone (Western Regional Climate Center, http://www.raws.dri.edu/, last accessed January 13, 2015), and Vermillion Weather Station (courtesy of Parks Canada, Kootenay National Park). All stations were within 5 km of the nearest burned edge. From the Vermillion weather station, we could only acquire daily mean temperatures, relative humidity, and average wind speed; therefore maximum and minimum values were not available and excluded from the analysis.

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

Topographic and landscape indices were evaluated, including potential incoming solar radiation summarized over one calendar year period (Fu and Rich 1999), elevation (m), slope (degrees; ESRI 2011), and steady state topographic wetness index (TWI). TWI was derived using Evans' (2003) script. Three topographic position indices including topographic position index (TPI), ridge/ridge-like position, and valley/valley-like position, were calculated within a 100-m neighborhood of each pixel using methods developed by Weiss (2001). The basic TPI calculation compares the elevation of each cell in a DEM to the mean elevation within the nearest-neighborhood of each pixel. Ridgetop or ridge-like positions are defined as positive TPI values (0-2.0), representing locations that are higher than the average of their surroundings, and valley or valley-like positions defined as negative TPI values (-2 to 0).

Data Analysis

We used Sequential Autoregression (SAR) analysis (Wimberly et al. 2009) to evaluate how previous burn severity, topography, vegetation, and weather, influenced burn severity. Our response variable was burn severity on each of our four study fires represented by continuous RdNBR or dNBR values. Candidate predictor variables included: weather variables, burn severity classification of past wildfire events (e.g., unchanged/unburned, low, moderate, and high), time since previous fire, topographic variables, vegetation types, and fuel characteristics (Table 1). We examined colinearity between possible predictor variables with simple pairwise correlations and excluded correlated variables (r >0.85; Nash and Bradford 2001) from the same model. The SAR models were constructed in R programming language (R Development Core Team 2011) and methods were published by Wimberly et al. (2009) and Prichard and Kennedy (2014). We compared individual variable models using Akaike's Information Criterion (AIC; Akaike 1974), and selected the final multivariate models based on lowest AIC values. We tested multiple models and removed variables when the AIC value was not reduced by more than 50 (Supplementary Table 1).

Prichard and Kennedy (2014) demonstrated that using a 30m nearest neighborhood distance minimized both AIC and Moran's I, and we confirmed with Moran's I that our final models did not have autocorrelation of the residuals at this neighborhood distance. Although SAR analyses define the SAR neighborhood weighted matrix by subsampling to reduce computational resources and time (Kissling and Carl 2008), we assigned point data information to each 30-m pixel across the entirety of each of our four study fires, including areas previously unburned. In the Cascade and East Zone Complex, a spatially continuous dataset was impossible due to a failure of the Landsat 7 EMT+ scan line correction mechanism (known as SLC off condition; Howard and Lacasse 2004; Supplementary Figure 1). In these two wildfires, we used all available points, skipping the 150-m scan line areas and treating pixels surrounding the scan lines as true neighbors. To address the possibility that missing data skewed results of our SAR analysis, we performed a test of bias by examining the distribution of cover type and topographic variables within these scan lines versus areas with RdNBR data. Our examination of pixels within and outside the scan lines showed that the distribution of canopy cover, elevation, slope, solar radiation and topographic wetness index were nearly identical for both the Cascade and East Zone

Complex fires (Figure 3), and therefore that there was no bias due to scan line errors.

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

Results

Final SAR models of burn severity, based on lowest AIC values, varied between study areas, but past burn severity was a strong predictor on all sites. The Tripod, Cascade and East Zone SAR models included distance to edge, valley bottom, maximum temperature, and cover type (Table 2 and 3). In addition to these common five variables, the final model for Tripod included canopy cover, elevation, and slope. The East Zone final model also included elevation, TWI, and maximum wind gusts on day of burning and the Cascade final model included slope, time since fire, maximum wind gusts on day of burning, and canopy cover. The Kootenay fire did not have vegetation variables; the final model included distance to edge, hill, elevation, average temperature and past burn severity. Many other predictor variables were significant predictors of RdNBR or dNBR but were not included in the final models, based on lowest AIC values.

Past wildfires

Past burn severity had a negative relationship on subsequent burn severity on all four study fires. Compared to areas unburned/unchanged in previous fires, previously burned pixels had reduced burn severity (Table 3, Figure 4). Areas that burned at high severity in the

Tripod and Kootenay fires contributed to the largest reduction in burn severity in the subsequent fire, while low burn severity areas had the smallest reduction or did not differ significantly from previously unburned/unchanged points. Conversely, on the East Zone and Cascade fires, areas that previously burned at low severity had the largest reduction in reburn severity compared to unburned areas.

Slightly different results were observed in the cover type models. The relationship to past burn severity was maintained within both low elevation and high elevation forest types on the Tripod, but the estimates on East Zone and Cascade fires varied from the full models. On the East Zone, high elevation forest types had the largest decreases in burn severity on sites previously burned at high severity, while low elevation forest types experienced the lowest burn severity after previously experiencing a low severity fire. On the Cascade fire the pattern was the same in both forest types: the lowest burn severity was observed after previously experiencing a low severity fire, while areas that experienced a high severity fire had significantly higher burn severity than unburned areas. (Table 4)

Distance to edge was a significant predictor and had a positive relationship on burn severity, reflecting that regardless of whether sites were previously burned, interior regions of these large fires had higher burn severity than the perimeters. This applied to all four fires we studied.

Time since past fire had mixed effects in the various models. On the Cascade fire burn severity was lower the longer time since fire, and though significant it was not included in the East Zone or Cascade models due to only small decreases in the best model AIC values. However, in the cover type models when forest types were analyzed individually, time since past fire proved to have a positive relationship on all three study areas (Table 4).

Fire weather, vegetation, and topography

Of the weather variables analyzed, the most important predictors of burn severity were maximum temperature and minimum RH on the Tripod, average temperature and average RH on the Kootenay, and maximum temperature and maximum wind speed on the East Zone and Cascade fires. Because temperature and relative humidity were highly and inversely correlated, only maximum temperature, the stronger of the two predictors based on lower AIC values, was included in the final model for the Tripod. Maximum temperature and maximum wind speed were included in the final model for the East Zone and Cascade. Burn severity was positively correlated with maximum temperature, but the relationship to maximum wind gust was mixed on the different study areas. On the East Zone Complex higher burn severity was correlated with higher maximum wind speeds, but a negative correlation was observed with burn severity on the Cascade Complex.

Of the LANDFIRE variables, vegetation canopy cover and cover type were the most important predictors of burn severity (Table 3). Forest canopy bulk density was also a significant predictor. However, because of the high correlation between canopy cover and canopy bulk density, only canopy cover was included in the final models. Valley bottom, ridge top, and TPI metrics were significant predictors of burn severity. Valley bottom, which was inversely correlated to ridge top, was included in final model for the Tripod, East Zone, and Cascade study areas because it was a better predictor. Valley bottom was inversely related to burn severity; valley bottoms burned less severely than ridges and steep slopes. TPI was highly correlated with both of these metrics and was therefore excluded in the final model on these three fires. On the Kootenay Fire, TPI was significant and the best predictor but was excluded from the final model because it only minimally reduced the model AIC value.

Elevation was a significant predictor of burn severity on the Tripod, East Zone, and Kootenay fires. Burn severity was positively correlated with elevation on these three fires, with increasing burn severity at higher elevations up to 2150 m on the Tripod, 2450 m on the

Cascade, 2550 m on the East Zone, and 2075m on the Kootenay. Above these elevations, burn severity decreased across the highest elevations of each fire area (Figure 5).

As slope and TWI were highly correlated, and slope was a slightly stronger predictor than TWI for the Tripod and Cascade (Table 3). Slope was positively related to burn severity on the Tripod and negatively related to burn severity in the Cascade and Kootenay. For East Zone, TWI was the stronger predictor and was inversely related to burn severity.

Discussion

Within each study area, top-down drivers such as weather (high temperatures, high windspeeds and low relative humidity) influenced fire effects as did bottom-up factors including topography, vegetation type and past wildfire effects (Parisien et al. 2011; Birch et al. 2015). Over the coming decades, the ecological footprint of heterogeneous burn severity patterns will contribute to the mosaic of vegetation response and will likely influence future landscape dynamics.

Evidence of self-regulation in past burns

The drivers of burn severity were remarkably similar across these four large and different landscapes, each with different land uses and fire history legacy. As these large fires burned across diverse topography and vegetation, burn severity generally was reduced by previous wildfires (Figure 4). Surface fuels and tree density, critical to fire behavior, were likely reduced on these previously burned areas (Stevens-Rumann and Morgan *in press*). Lower fuel connectivity may have led to associated reductions in subsequent fire behavior and effects (Alexander and Cruz 2012). While the reduction in fuel may be beneficial from a fire suppression stand point, these changes in fuel may indicate large changes in vegetation type (e.g. Stevens-Rumann and Morgan *in press*; Harvey et al. 2016)

Although lower burn severity was observed in previously burned areas on all four study sites, the impact of prior burn severity varied by study site (Figure 4a and b). The results from Tripod and Kootenay directly contrasts with recent studies in which low to moderate previous burn severity resulted in a reduction in subsequent burn severity but high severity fires were often followed by high severity fires (Collins et al. 2009; Holden et al. 2010; Parks et al. 2014a; Harvey et al. 2016). Differences may be explained by slow vegetation response in the Tripod and Kootenay compared to other study locations, such as Yosemite National Park, where flammable shrub fields can regenerate rapidly following high burn severity fire (Collins et al. 2009; van Wagtendonk et al. 2012). Another potential reason for this difference may be that our study areas are outside of wilderness and experienced different fire suppression actions and prior land uses. Fire suppression on the edge of the past fires, including containment lines and burnout operations, may have effectively reduced fire spread and/or decreasing subsequent burn severity, especially within older wildfires. We could not account for this except with our distance to edge metric due to the lack of geospatial data of fire suppression activities.

In forested cover types, burn severity increased as the time since fire increased on all study fires, and this relationship was generally strongest in dry forest types (Table 4), as was reported by others (Holden et al. 2010; Haire et al. 2013; Parks et al. 2014). In these ecosystems with shorter fire return intervals, previously burned areas only act as barriers or mitigate burn severity for short periods of time due to rapid accumulations of grasses, other herbs, shrubs and fine wood (e.g. Peterson 2002; Parks et al. 2015).

Patches of stand-replacing fire or areas maintained by frequent surface fires create fuel heterogeneity that may reduce subsequent fire spread or burn severity (Hessburg et al. 2015). The marked decrease in burn severity across most previously burned areas supports this concept. In both high elevation, moist forests and low elevation, dry forests on the East Zone, Tripod, and Kootenay Fires, high burn severity in an initial fire resulted in lower burn severity in subsequent fires, with the exception of forested cover types on the Cascade.

Although other variables were also important to our predictive models of burn severity, large decreases in burn severity associated with previous severity indicates that these altered landscapes are less likely to burn severely again within the first two decades following a fire (Hudak et al. 2010; Prichard and Kennedy 2014; Harvey et al. 2016).

The capacity of past burn mosaics to self-regulate is not well understood given the deficit of fire in many dry forest landscapes over the past century (Hessburg et al. 2007; Marlon et al. 2012). Fire on fire interactions are still relatively uncommon across dry forest landscapes but will become more prevalent in the coming decades as wildfires continue with warmer, drier summers predicted for much of the western United States (Littell et al. 2009; Cansler and McKenzie 2014). The amount of area reburned in our study landscapes was small (roughly 3% of the total fire area), but proportion of areas reburned will likely increase with climate change. Fire activity has already dramatically increased in the past decade, with 3.7 million ha burned nationally in 2015, 45% more than the previous 10-year average (http://www.nifc.gov).

Because previous wildfires mitigated burn severity under extreme conditions, we expect past wildfires to be particularly effective at shaping landscapes when subsequent fires burn under less extreme fire weather (Pollet and Omi 2002). Past wildfires can alter burn severity and even fire spread, acting as temporary fuel breaks (Teske et al. 2012; Haire et al. 2013; Parks et al. 2014, 2015), and a single fire may be sufficient to initiate self-regulation. However, large stand-replacing wildfires also may result in a large, homogenous area of similar fuels that, in the absence of subsequent finer-scale disturbances, could predispose landscapes to subsequently large fire events that further homogenize landscapes (Peterson 2002). Smaller fires, in particular, may be critical to creating landscape patterns that would be less conducive to burning in subsequent large, stand-replacing events (Hessburg et al. 2015) and prevent large vegetation type conversions (Harvey et al. 2016; Stevens-Rumann and Morgan *in press*). Currently, a common fire management strategy is to suppress all wildfires. However, fires that burn under mild or average weather conditions may provide critical heterogeneity in vegetation cover and structure that mitigates area burned and patterns of burn severity in subsequent wildfires (Hessburg et al. 2015, Kemp et al. 2015).

Fire weather

In general, higher temperatures, lower relative humidity and in some cases stronger winds were related to higher burn severity (Table 3). Our results suggest that on more extreme weather days, fires burn more severely, fueled by reduced thresholds to burning and the influence of wind on fire spread and intensity (Birch et al. 2015; Cansler and McKenzie 2014). The weather variables, broadly summarized from nearby weather stations, in the final models suggests that nearby weather stations may be a decent proxy for finer-scale, fire-weather relationships (Prichard and Kennedy 2014). However, we found some inconsistent relationships: on the East Zone fire burn severity increased with higher winds, while the opposite relationship was observed on the Cascade. Fine-scale variability in weather patterns were undetectable using coarse-scale data and may be the reason for this inconsistent relationship (Taylor et al. 2004). Although progression maps allowed us to relate burn severity at a pixel to the weather at the general time of burning, progression intervals varied from < 24 hours to four days of burning, and the weather conditions at the time a given pixel burned could be poorly represented by summarized weather over the progression interval.

Vegetation

Denser, closed-canopy forests burned at higher severity than open canopy forests, as would be expected from past studies (Schoennagel et al. 2004). Severity was highest in the high elevation forest types (Table 3 and 4). Multi-layered, conifer forests dominated by thin-barked trees burn with a higher proportion of high severity, stand-replacing fires and are characterized by either mixed or high-severity fire regimes (Bigler et al. 2005; Prichard and

Kennedy et al. 2014). In contrast, dry, low elevation forest types (i.e., dry-mesic mixed-conifer, ponderosa pine, Douglas-fir cover types) generally burned at lower burn severity on the Tripod, Cascade, and East Zone fires.

Burn severity in grasslands and shrublands was more severe than dry-mesic mixed conifer forests. Given the variation among and within these grouped vegetation types from alpine meadows to low elevation grasslands/shrublands interpretation may be difficult and skew relationships with burn severity. Additionally, burn severity is known to be difficult to infer from satellite imagery one-year post-fire in many of these grass and shrub cover types given the rapid vegetation recovery within one year (van Wagtendonk et al. 2012).

Topography

Across study sites, we found that burn severity was related to topographic variables including slope gradient, elevation and TWI (Table 3). Across all sites, burn severity increased as slope gradient increased, which is corroborated by other studies (e.g. Birch et al. 2015). Burn severity decreased as TWI increased, similar to other studies (Holden et al. 2009). These relationships may be related to changes in fire behavior across topographical and moisture gradients. As wildfires spread up steep, drier slopes, fire intensity generally increases, transition from surface to crown fire is more possible, and rate of spread and flame lengths increase (Scott and Reinhardt 2001). Airflow in valley bottoms is also sometimes restricted and may be related to generally lower burn severity in valley-like settings (Finney and McAllister 2011).

The positive correlation between burn severity and elevation is likely a result of fuel moisture gradients and differences in vegetation types. Low elevation areas of the Cascade, East Zone and Tripod fires were dominated by relatively fire-resistant, thick-barked species such as ponderosa pine and mature Douglas-fir. Conversely, mid- to high elevation areas were dominated by higher density mixed conifer forests dominated by thin-barked species such as lodgepole pine and subalpine fir that are more readily killed by even low intensity fires (Agee 1999). Across forested areas of the western US, as elevation increases so do fire return intervals and the proportion of high burn severity when fires occur (Schoennagel et al 2004).

The highest elevations in our study areas generally had low burn severities that were comparable to the burn severity of low elevation sites (Figure 5). Subalpine and alpine areas often have higher fuel moisture, lower temperature, higher relative humidity, and less burnable vegetation at or above tree line (Schoennagel et al. 2004). Reduced burn severity at the highest elevations was especially demonstrated in the Kootenay and Tripod study areas. On the Kootenay fire, burn severity declined above approximately 2100 m elevation. On the Tripod Complex, post-burn imagery indicated that subalpine meadows did not burn; the subsequent fires burned around subalpine meadows or only consumed tree islands within them.

Conclusions

Our study provides strong evidence that the landscape patterns created by past wildfires influenced subsequent wildfire burn severity, creating a landscape legacy of burn mosaics. While many factors influence burn severity, previous wildfires reduced burn severity on all four subsequent large fires. Considering the extreme fire weather under which these fires burned, it is important to note that the bottom-up factors of past fires, vegetation, and topography influenced burn severity. Our research supports the consideration of managing wildfires to burn into previously burned landscapes as these may continue to reduce burn severity under most fire weather conditions and allow fire to return to fire-prone landscapes (Hessburg et al. 2015).

Because we studied wildfires in non-wilderness areas, the study areas provide some insights into the influence of past wildfires during operational management of on-going, large wildfires. For example, during the 2003 Kootenay Fires, the 1968 Vermillion Fire was effectively used in a burnout operation to halt the eastward spread of Kootenay Complex into old-growth Engelmann spruce and subalpine fir forests of the Bow Valley and Banff National Park (Rick Kubian, Parks Canada, personal communication). Fires in Idaho in recent decades have been extensive, with over 46% of the Boise National Forest burned since 1984. In response, some incident management teams are making strategic decisions to take advantage of where previous fires may limit the spread of subsequent fires (Bob Schindelar, Boise National Forest, personal communication). Likewise, even during large fire spread days, the 2006 Tripod Complex fire was corralled by several recent wildfires that occurred from 1994-2003 and even the 1970 Forks fire which was composed of young, regenerating lodgepole pine with sparse surface fuels (Gray and Prichard 2015). Following the 2006 Tripod fire, two subsequent wildfires, including the 2014 Carlton Complex and the 2015 Okanogan Complex, shared borders with the Tripod perimeter and these were the only parts of the fire complexes that were not actively suppressed. Incident command communicated to the public that there were insufficient fuels to carry active fire spread within the Tripod burn area, and while the wildfires burned to the edge of the Tripod burn area, they did not advance into the recently burned landscapes.

Previously burned areas are considered in both active fire management (http://wfdss.usgs.gov/wfdss/WFDSS_Home.shtml last accessed 28 June 28, 2016) and in achieving land management goals. Given the rising cost of fire suppression (Calkin et al. 2015), knowing when and where areas are expected to burn less severely can help to reduce the costs of future large wildfire events while assisting land managers in making the fire management decisions consistent with land management plans and restoration priorities (Hessburg et al. 2015). Wildfires, even the large fire events studied here, possess some attributes of self-regulation, and managing for the interaction of these events can contribute to restoring the resilience of fire-prone landscapes. Allowing more wildfires to burn, especially in dry forest types, may not only serve land management by potentially mitigating future burn severity, but also promote more fire resilient landscapes that can withstand the impacts of repeated disturbances that will become ever more present with climate change.

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TABLES

Table 1. Candidate predictor variables for sequential autoregression (SAR) modeling for the four study areas (Tripod, Cascade, East Zone, and Kootenay*).

Variable	Definition
Wildfire data	
PastSev-Past burn severity	Categorical RdNBR (unburned/unchanged, low, moderate, high)
Edge-Distance to edge (m)	Distance from study fire perimeter
TSF-Time since previous fire	Number of years since each pixel burned
Fire weather	
MaxTemp-Maximum temperature (°C)	Maximum temperature over progression interval
AvgTemp-Average temperature (°C)	Average temperature over progression interval
MaxGust-Maximum wind speed (kph)	Maximum recorded wind over progression interval
AvgGust-Average wind speed (kph)	Average wind speed over progression interval
MinRH-Minimum RH (%)	Minimum relative humidity over progression interval
Vegetation	
CBD-Canopy bulk density (kg m^3)	Bulk density of available canopy fuel
CovType-Cover Type	Derived from existing vegetation type
CC-Canopy Cover (%)	Canopy cover of vegetation
Topography	
Elev-Elevation (m)	National elevation dataset
Slope (degrees)	Slope gradient
Solar radiation (WH m^{-2})	Potential incoming solar radiation (no cloud cover)
TWI- Topographic wetness	Topographic Wetness Index
TPI-Topographic position index	Discrete classified TPI raster
Valley	Fuzzy valley bottom or 'valley-like' position
Ridgetop	Fuzzy ridgetop or 'ridge-like' position

* Due to the fairly uniform vegetation types and stand structures on the Kootenay we did not include vegetation characteristics for this model.

Table 2. Final sequential autoregression full models of relative differenced Normalized Burn Ratio (RdNBR) for the Tripod, Cascade, East Zone, and differenced Normalized Burn Ratio (dNBR) for the Kootenay study areas. N is the number of points analyzed.

Model	Predictor variables	N	R^2	AIC
Tripod	CC, CovType, Edge, Elev, MaxTemp, PastSev, Slope, Valley	326,541	0.92	4,884,497
East Zone	CovType, Edge, Elev, MaxGust, MaxTemp, PastSev, TWI, Valley	905,805	0.73	12,705,742
Cascade	CC, CovType, Edge, MaxGust, MaxTemp, PastSev, Slope, TSF, Valley	975,414	0.77	13,736,440
Kootenay	AvgTemp, Edge, Elev, Slope, PastSev	88,272	0.90	1,080,976

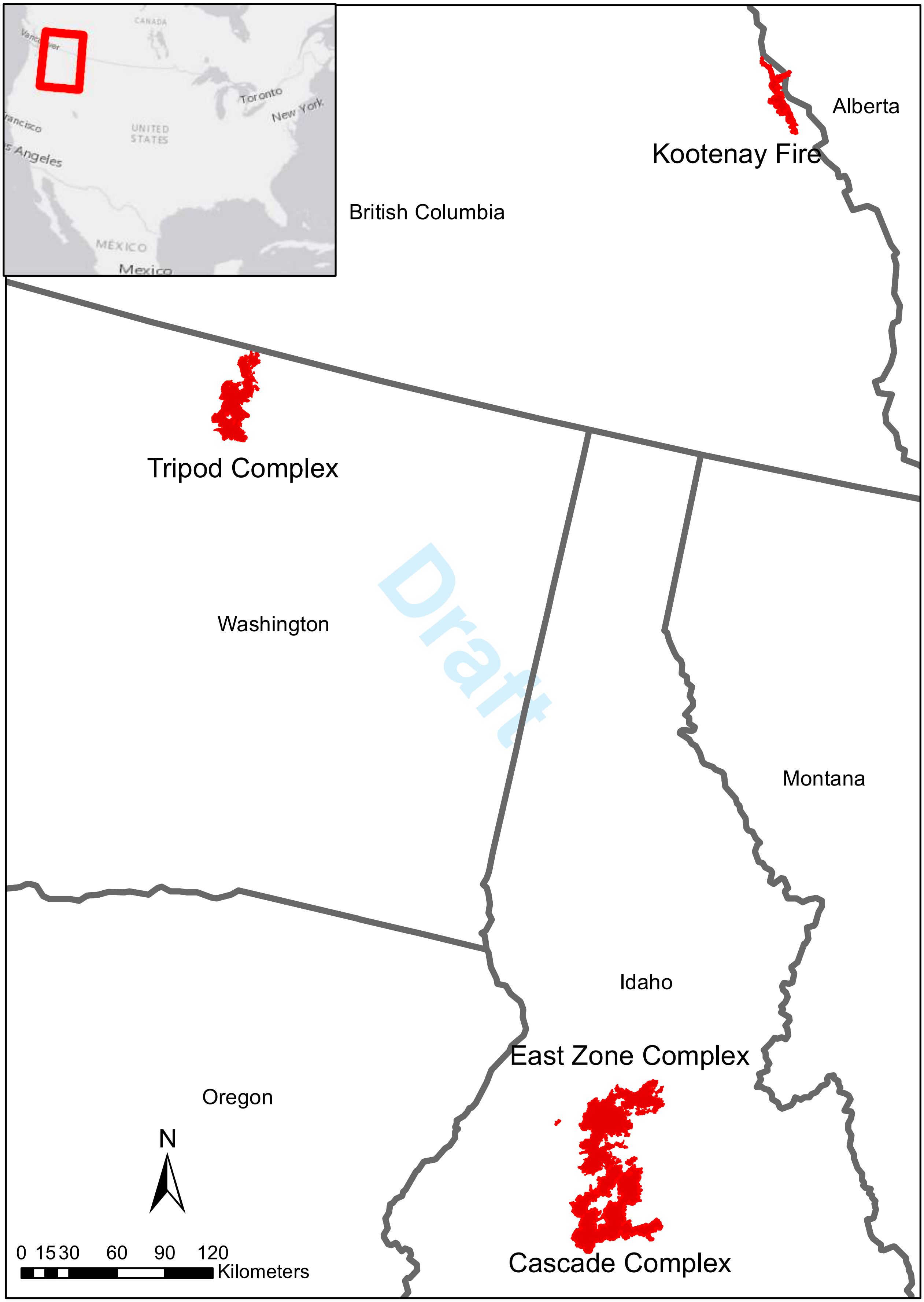
Table 3. Outputs for final SAR model for each variable. Past burn severity (PastSev) was categorized into unburned/unchanged (as the baseline), low, moderate, and high according to thresholds in Miller and Thode (2007). Cover type (CovType) was categorized into dry-mesic mixed conifer (DMC; as the baseline), douglas-fir/hemlock (DFHE), grassland/shrubland (GRASS/SHRUB), lodgepole pine dominated (LP), ponderosa pine dominated (PP), riparian areas (RIP), and subalpine fir dominate (SUBALP). Relationship to burn severity is distinguished by the "estimate," with the standard error (SE) and p-value (P), indicated for each variable.

	Tripod			East Zone			Cascade			Kootenay		
Variables	Estimate	SE	*P*	Estimate	SE	*P*	Estimate	SE	*P*	Estimate	SE	*P*
Intercept	-428.00	29.40	<0.0001	-71.43	7.37	<0.0001	704.00	31.60	<0.0001	129.60	36.78	0.0004
Edge	0.13	0.01	<0.0001	0.03	0.01	<0.0001	0.04	0.01	<0.0001	0.18	0.008	<0.0001
Valley	-0.12	0.02	<0.0001	-0.52	0.02	<0.0001	-0.67	0.25	<0.0001	-	-	-
MaxTemp	1.57	0.09	<0.0001	3.42	0.13	<0.0001	7.30	0.20	<0.0001	-	-	-
AvgTemp	-	-	-	-	-	-	-	-	-	8.23	0.79	<0.0001
Past Sev – Low	-16.60	2.12	<0.0001	-16.85	1.29	<0.0001	-284.00	27.50	<0.0001	0.42	7.84	0.96
Past Sev – Moderate	-28.90	2.71	<0.0001	-17.00	1.76	<0.0001	-266.00	27.40	<0.0001	-19.68	8.83	0.03
Past Sev – High	-42.10	3.18	<0.0001	-25.50	2.40	<0.0001	-246.00	27.50	<0.0001	-54.16	13.58	<0.0001
Slope	1.38	0.13	<0.0001	-	-	-	-0.48	0.11	<0.0001	-0.18	0.04	0.03
TWI	-	-	-	-5.15	0.18	<0.0001	-	-	-	-	-	-
CovType DFHE	4.44	8.16	0.59	7.08	1.45	<0.0001	0.34	2.69	0.90	-	-	-
CovType GRASS/SHRUB	3.48	1.42	0.014	13.90	1.74	<0.0001	8.10	2.91	0.005	-	-	-
CovType LP	2.45	0.91	0.0070	7.72	1.86	<0.0001	8.84	2.84	0.002	-	-	-

CovType PP	-6.01	2.81	0.033	3.09	2.08	0.13	-2.41	4.40	0.58	-	-	-
CovType RIP	-44.60	3.02	<0.0001	-1.58	2.85	0.58	-8.36	3.53	0.02	-	-	-
CovType SUBALP	2.93	0.89	0.0010	10.20	1.66	<0.0001	10.90	2.79	<0.0001	-	-	-
Elev	0.47	0.02	<0.0001	0.31	0.01	<0.0001	-	-	-	0.094	0.019	<0.0001
CC	0.70	0.03	<0.0001	-	-	-	6.44	0.027	<0.0001	-	-	-
MaxGust	-	-	-	1.26	0.23	<0.0001	-3.55	0.20	<0.0001	-	-	-
TSF	-	-	-	-	-	-	-3.30	0.31	<0.0001	-	-	-

Table 4. Results of cover type SAR analysis, performed on points identified as a "low elevation forest type" (Douglas-fir/hemlock, ponderosa pine, dry-mesic mixed-conifer) and a "high elevation forest type" (lodgepole pine, subalpine fir). Values are the regression estimate of time since fire and past burn severity (low moderate, high) in comparison to previously unburned/unchanged points. Asterisks indicate significance at α=0.05 level.

Area	Elevation (Forest type)	time since fire	Past severity-low	Past severity-moderate	Past severity-high
Cascade	High	0.09*	-15.88*	-1.71	22.01*
	low	0.23*	-29.20*	-14.91*	17.08*
East Zone	high	0.63*	-49.92*	-64.01*	-71.58*
	low	0.41*	-36.30*	-37.07*	-29.61*
Tripod	high	1.30*	-100.08*	-188.58*	-281.46*
	low	5.28*	-378.03*	-465.61*	-520.36*


CANADA
Toronto
New York
UNITED STATES
Los Angeles
MÉXICO
Mexico
British Columbia
Alberta
Kootenay Fire
Tripod Complex
Washington
Montana
Idaho
Oregon
East Zone Complex
Cascade Complex
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0 15 30 60 90 120
Kilometers
Draft

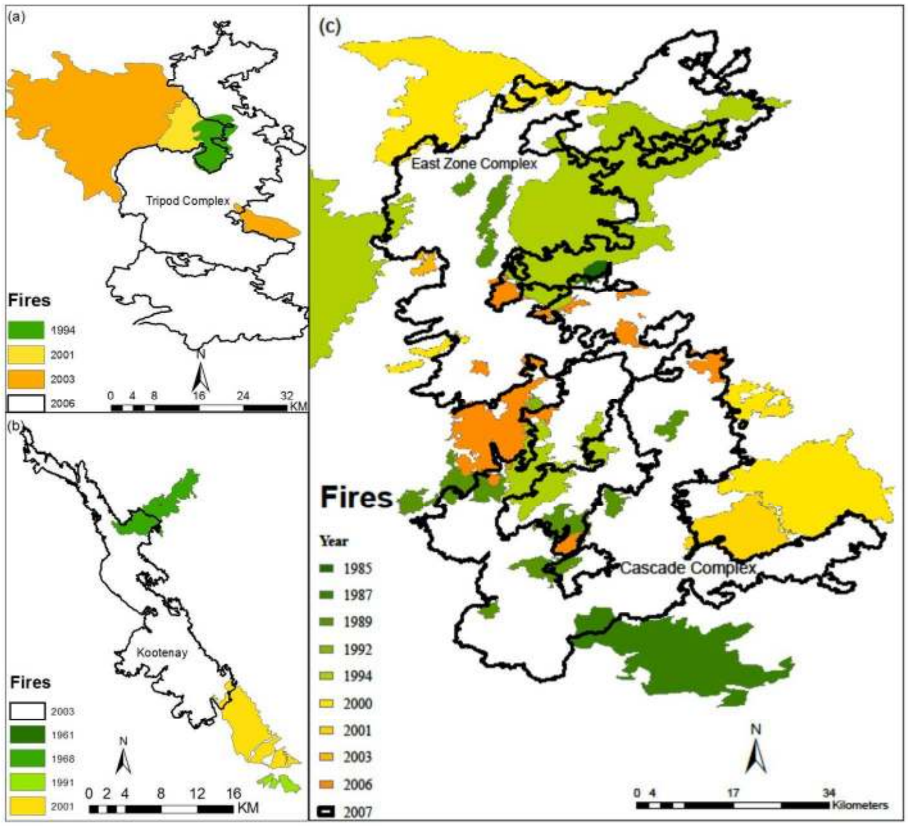


Figure 2. (a) Tripod Complex, (b) Kootenay Fire, (c) East Zone Complex and Cascade Complex with perimeters of previous wildfire. Older past fires are indicated with greens, while more recent fires are indicated in orange and yellows.

287x274mm (150 x 150 DPI)

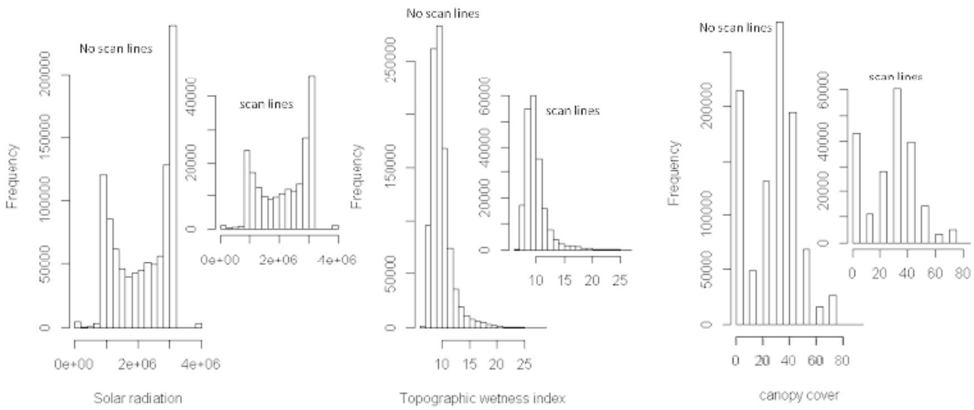


Figure 4.

Figure 3. Distribution of topographic (solar radiation and topographic wetness index) and vegetation (canopy cover) variables using our East Zone dataset which excluded the scan lines compared to a dataset of the pixels within the scan lines which we were unable to use due to lack of burn severity information. Distributions are very similar for both, reducing the possibility of bias with the missing data.

304x139mm (150 x 150 DPI)

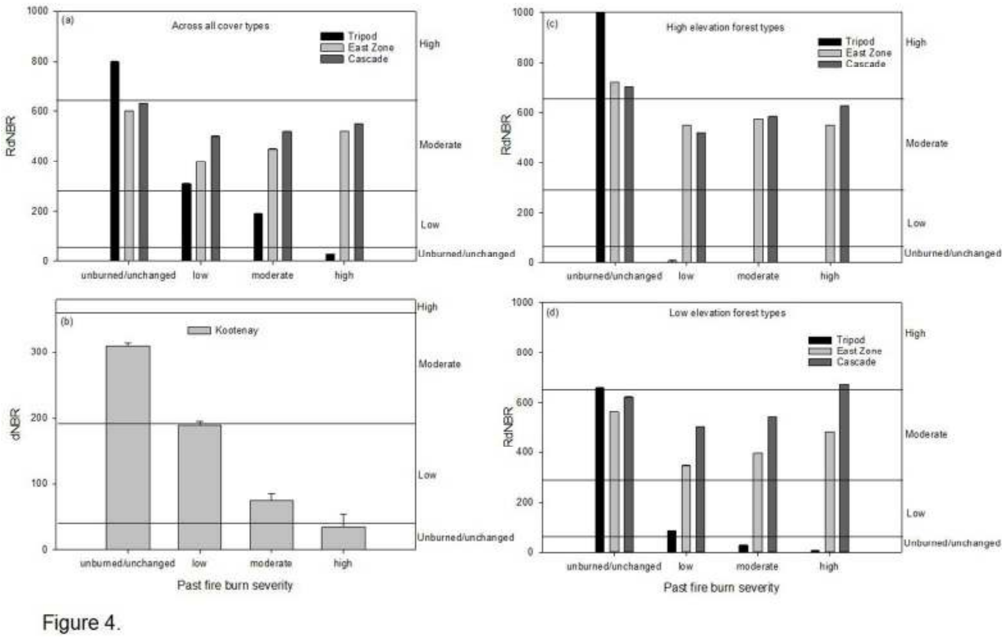


Figure 4. RdNBR or dNBR response by past fire burn severity on each fire. The left axis is a continuous RdNBR/dNBR metric, while the right axis identifies the burn severity thresholds we used based on Miller and Thode (2007) of unchanged/unburned, low, moderate, and high severity. (a) is the RdNBR response to burn severity on the Tripod (black), East Zone (light gray), and Cascade (dark gray) Fires across all cover types. (b) is the dNBR response to past burn severity on the Kootenay Fire. (c) is the RdNBR response to past burn severity in "high elevation" forest types. (d) is the RdNBR response to past burn severity in "low elevation" forest types.

225x150mm (150 x 150 DPI)

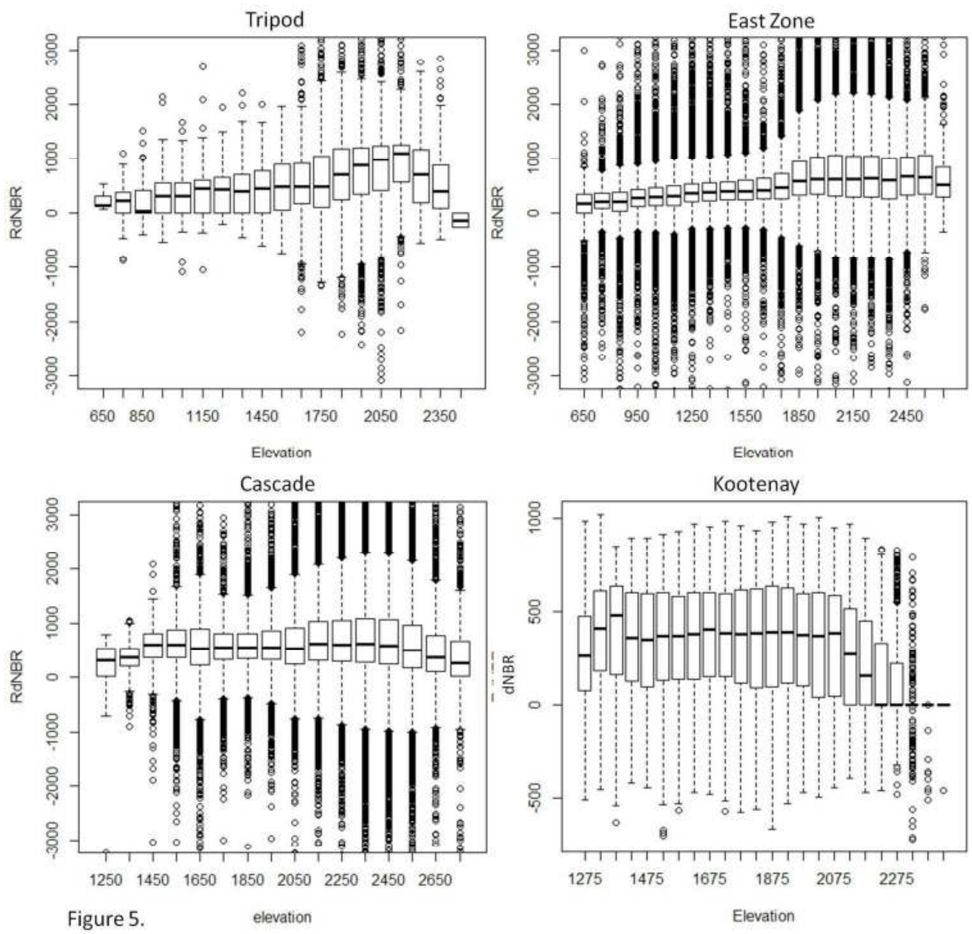
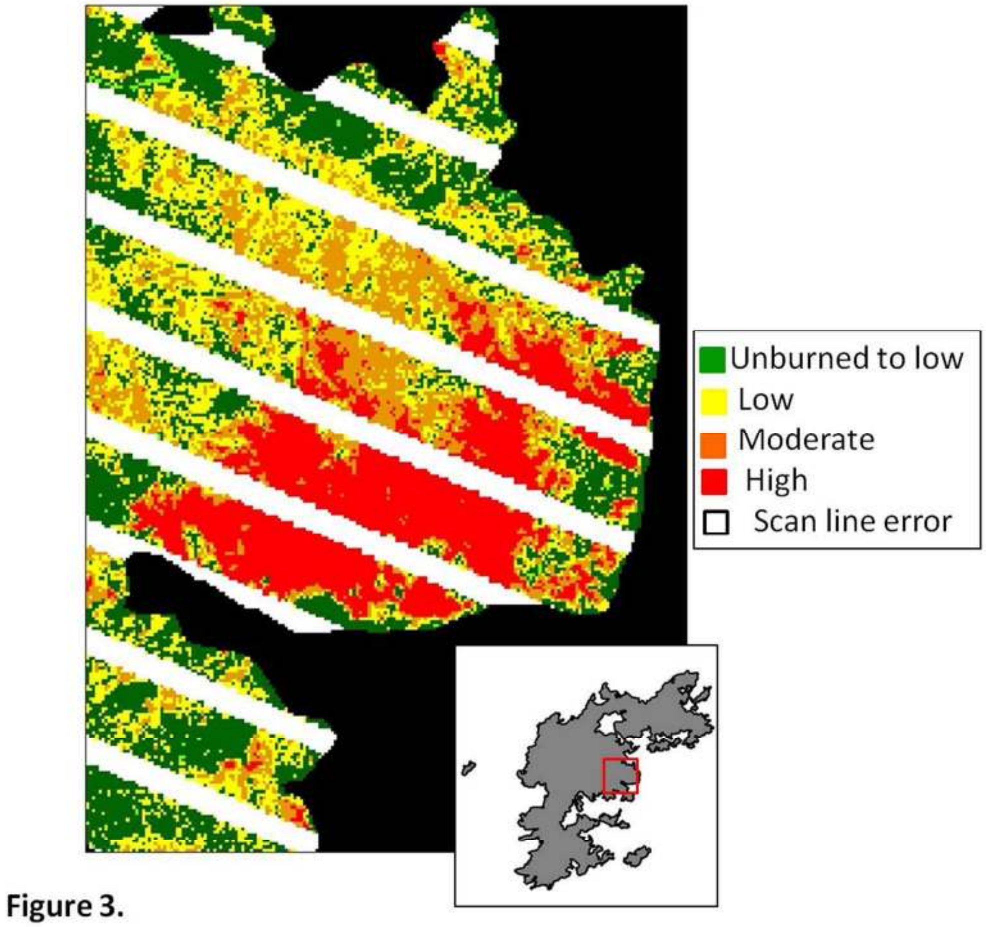


Figure 5. Box and whisker plots of RdNBR and dNBR response by elevation. Tripod is in the top left, East Zone in the top right, Cascade on the bottom left, and Kootenay in the bottom right.

282x277mm (150 x 150 DPI)



Supplemental Figure 1: Example of scan line errors in the Landsat satellite data on the East Zone Complex Fire. White lines indicate missing data; lines are 150 m wide.

187x190mm (150 x 150 DPI)