Title
On the causes of the summer 2015 Eastern Washington wildfires

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Publication Date
2018

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA

Los Angeles

On the causes of the summer 2015 Eastern Washington wildfires

A thesis submitted in partial satisfaction

of the requirements for the degree of Masters of Arts

in Geography

by

Ruth Aliza Engel

2018

ABSTRACT OF THE THESIS

On the causes of the

summer 2015 Eastern Washington wildfires

by

Ruth Aliza Engel

Master of Arts in Geography

University of California, Los Angeles, 2018

Professor Dennis P. Lettenmaier

In the summer of 2015, Eastern Washington experienced over 2000 fires that burned in excess of 450,000 ha, took the lives of three firefighters, and caused hazardous air quality throughout much of the region. In Eastern Washington, summer 2015 was nearly 1ºC warmer than the previous record warm year and 1.4ºC warmer than climatology. Dead Fuel Moisture (DFM) in summer 2015 was near the extreme low of record. We examine both Washington's 2015 fire season and the 32-year fire record with respect to temperature and precipitation climatology and other potential drivers of fire. We find that the extreme 2015 fire year was not attributable to any one physical factor, but rather to a combination of anomalously dry and warm summer conditions, a lightning storm in mid-August, and possibly the encroachment of invasive

cheatgrass. These risk factors combined to drive large fires that propagated quickly, mostly through grasslands and into forested areas.

The thesis of Ruth Aliza Engel is approved.

Thomas W. Gillespie

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2018

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ACKNOWLEDGEMENTS

This manuscript has been submitted as “On the causes of the summer 2015 Eastern Washington wildfires” with co-authors Miriam E. Marlier and Dennis P. Lettenmaier. The work was supported in part by Grant No. NA14OAR4310293 from NOAA’s Modeling, Analysis, and Prediction Program to the University of California, Los Angeles. Thanks Leroy Westerling and Robert Field for discussions and suggestions at the early stage of this research.

1 Introduction

According to the Northwest Interagency Coordination Center (NWCC), the summer of 2015 in the Pacific Northwest (Washington and Oregon) was "the most severe fire season in modern history" [*NWCC* 2015]. Almost 500,000 ha in Eastern Washington (which we define as that part of Washington State east of 122ºW longitude) burned from May to September, almost five times the average over the previous 31 years. Over 2000 fires were reported in Eastern Washington, of which over 50 were classified as large (>100 acres of forest or >300 acres of grassland) [*NWCC* 2015]. During the period from August 20th to September 1st, 2015, air quality in Eastern Washington was consistently unhealthy according to the US Environmental Protection Agency [*NWCC* 2015].

Over the last three decades, wildfires of all sizes have become more common in the Western US [*Westerling* 2006; *Stavros* et al. 2014]. Westerling et al. [2006] argue that a general warming trend and earlier spring snowmelt are associated with increased fire incidence, and Littell et al. [2009] and Westerling et al. [2003] found that fires are more common during drought conditions. Historical correlations between burn severity indices and fire occurrences suggest that the primary drivers of severe fire seasons are warm temperatures and (lack of) precipitation as well as fuel availability, wind, and humidity. Land cover also plays a role; different ecosystems have varying levels of fuel availability, which dry at different rates during warm summer months [*Westerling,* 2003]. The Western US has experienced droughts due to winter (December to February) warming, evidenced by diminished spring snowpacks that reduce summer water availability [*Mote et al.* 2005]. As a result, burned area in the Western US is expected to continue to increase over the next century as the climate continues to warm [*Littell et al*. 2010].

We investigate here possible drivers of the exceptional 2015 wildfire season in Eastern Washington relative to the previous 31 years for which good data on the spatial extent of burns are available. In particular, we investigate the role of drought conditions associated with the anomalously warm winter of 2014-15, fuel moisture, and ignition sources. We also consider other factors, including forest damage, propagation, and encroachment of invasive species (mostly cheatgrass) in the grassland portion of the region, that might have played a role in the extreme fire season.

2 Methods

We calculated burned area over Eastern Washington (east of 122º; see Figure 1) between 1984 and 2015 to determine the summer 2015 anomaly. To establish drivers of the extreme fire season, we examined climatic and non-climatic factors that potentially influenced fire fuel load, ignition, and propagation.

2.1 Burned Area

Our primary source of burned area information was the Monitoring Trends in Burn Severity (MTBS) database, produced by the US Geological Survey and the US Forest Service [*Eidenshink et al.* 2007; https://www.mtbs.gov/]. MTBS uses fire incident reports from state and federal agencies and calculates pre- and post-fire Normalized Burn Ratios (NBR) for burned regions. NBR values are calculated using 30 m Landsat near infrared and shortwave infrared bands to emphasize contrast between healthy and burned vegetation. The pre-fire and post-fire NBR values are compared to isolated burned area perimeters. Burned areas so identified are further classified as wild or prescribed [*Eidenshink et al.* 2007]. We used MTBS as our primary data resource because it is consistently available for a longer time period than other sources (1984 through 2015) and because fire perimeters are manually corrected to match state and federal fire report data [*Eidenshink et al.* 2007].

To cross-check the MTBS data over our study domain, we used NASA's Fire Information for Resource Management System (FIRMS), which consists of fire hotspots representing the centroids of 1 km MODIS Terra and Aqua pixels that show evidence of thermal anomalies in brightness temperature. FIRMS data are continuous from 2000 through 2015 [*Davies et al.*, 2009]. They cover a shorter historical period than MTBS because they are based on MODIS satellite data, which began with the launch of NASA's Terra satellite in 2000. For 2015, we also compared MTBS estimates with fire perimeters from the USGS Geospatial Multi-Agency Coordination Group (GeoMAC) [*Walters et al.* 2008]. The GeoMAC data use fire reports submitted by state and federal agencies across the conterminous US and Alaska to compile daily burned area perimeters based on GPS data, fixed-wing aerial and MODIS imagery, and NOAA's Geostationary Operation Environmental Satellite (GOES) hazard mapping system. We compared MTBS burned area with FIRMS points and GeoMAC area across the Pacific Northwest (Figure A1), and found that the two generally are spatially and temporally consistent. The MTBS trends match well with FIRMS fire counts. In particular, 2015 is consistently anomalous across all datasets within our study domain (Figure A1).

We focused our analysis on Eastern Washington, which showed both the largest burned area and the highest number of fires in 2015 among the northwestern states. We defined our domain as the area of Washington State east of 122º, where the number and extent of fires were largest. This portion of Washington, where most of the fires occurred, is managed by a combination of entities including the US Forest Service (USFS), the Bureau of Indian Affairs, the Washington Department of Natural Resources, the US Fish and Wildlife Services, and private owners [*USGS,* 2017].

2.2 Climatic Drivers of Fire Risk

Examined annually or seasonally, temperature and precipitation alone generally have low correlations with fire occurrence [*Littell et al.,* 2010; *Westerling et al.,* 2006]. Previous studies of fire in the Western US have, however, found statistically significant correlations between fire indices and the combined influence of metrics related to temperature and precipitation, such as the Palmer Drought Severity Index [*Westerling et al.,* 2003], composite variables such as length of the spring growing season [*Littell et al.* 2009], or combined summer temperature, precipitation, and previous winter's snowpack [*Littell et al.,* 2010]. To account for the role of multiple physical climate and hydrological variables affecting fire vulnerability, we used the US Forest Service Dead Fuel Moisture (DFM) content [*Cohen and Deeming,* 1985].

Following Gergel et al. [2017], we calculated DFM at a 1/16º spatial resolution using the Livneh et al. climate data set [*Livneh et al.,* 2015] from 1950-2015 (see also [*Marlier et al.,* 2017]). DFM quantifies fire danger by establishing a maximum and minimum daily equilibrium moisture content (EMC) of dead material in steady-state conditions based on temperature, precipitation, and relative humidity [*Cohen and Deeming,* 1985]. DFM content itself is calculated based on fuel class. Here, we used 1- and 10-hour time lags for grassland areas, which are applicable to fuel under 1 inch in diameter, and 100- and 1000-hour time lags for forested areas for fuel sizes of 1-8 inches in diameter. Smaller time lags respond more quickly to changing environmental conditions [*Cohen and Deeming,* 1985]. Previous studies have demonstrated correlations between summertime DFM and large fires across the Northwest [*Stavros et al.,* 2014]. To calculate DFM, we used gridded daily precipitation, maximum and minimum temperature, and specific humidity, where specific humidity was estimated using MTCLIM algorithms as described by *Livneh et al.* [2013; 2015] and *Bohn et al.* [2013].

2.3 Non-Climatic Drivers

2.3.1 Land Cover

Our primary source of land cover data was the Multi-Resolution Land Characteristics Consortium's 2011 National Land Cover Database (NLCD), which classifies land cover into 16 categories at a 30 m spatial resolution [*Homer,* 2012]. We examined MTBS polygons across land cover classes to compare forested and grassland burned area. Additionally, we classified FIRMS active fire directions by land cover class to evaluate propagation of individual fires across forests and grasslands. We relied on the 2011 NLCD because of its high resolution and because forest-grassland interfaces did not change substantially over the study period.

To verify consistency in land cover, we examined forest change across our domain using the Global Forest Change database v1.2 [*Hansen et al.,* 2013], which compares Earth observation satellite images (primarily from Landsat) over time to measure losses in forest cover from 2000-2014 and gains in forest cover from 2000-2012 (although more recent data are available on forest gains, as of this writing the forest loss data end in 2012). Forest loss data are available through 2015, but almost exclusively reflect the summer fire season. Accordingly, we limited forest change analysis through 2014.

2.3.2 Forest Health

We examined forest health using the Aerial Insect and Disease Survey (ADS) GIS data for Washington, collected from the US Forest Service Aerial Detection Survey [*USFS,* 2016]. ADS surveys are conducted by manually observing forest damage from a high-winged aircraft and recording specific damage sites on a map, and cover the forested areas of our domain.

Flyovers in Washington are conducted annually (1947-2016), and forest damage is recorded at a quarter-tree scale [*USFS,* 2016]. We evaluated whether spatial correlations exist between 2015 burned area in regions covered by the ADS flyovers and 2014-2015 forest damage.

2.3.3 Ignition

Because no quantitative data on long-term ignition trends across our study domain were available, we drew on ignition data (2005-2015) from the NWCC annual reports. NWCC reports list the number of fires fought and total area burned in the domain of each reporting agency according to ignition source (human or lightning). We evaluated burned area and fire counts with respect to ignition sources, and applied NWCC data to MTBS burned area maps to examine spatial and temporal ignition trends within the 2015 fire season.

Additionally, we investigated the role of wind in initial transmission of fires and the development of a mid-August cold front using the Washington State University Agweather services, which isolates trends from individual weather stations [*Agweather* 2017; https://weather.wsu.edu/]. We examined 16 weather stations in Eastern Washington grasslands with available August 2015 data to understand the role of wind in the timing of ignition.

2.3.4 Propagation

We examined propagation of large fires using FIRMS points, which are based on the centroids of 1 km MODIS pixels that contain active fires. We tracked the sub-daily progression of FIRMS points from each MODIS overpass by coding each FIRMS active fire point according to both NLCD land cover type and individual MTBS fire perimeter so as to get a pixel-level categorization of land classification. We then examined hotspot transmission across land cover type for each large fire in 2015, and evaluated whether early propagation was primarily through grassland or forest. Additionally, we reviewed the encroachment of invasive species, particularly cheatgrass (*Bromus tectorum*), as a potential driver of rapid grassland propagation.

3 Results

The summer of 2015 had a 32-year burned area anomaly of 6.8 relative to the MTBS 1984-2015 record for the study area (i.e., the 2015 burned area was 6.8 times the 1984-2015 mean; Figure 2). Summer 2015 also had the highest fire counts in the study period (Figure A1). The Okanogan Complex Fire, which dominated the northern forested part of the domain, was the largest individual fire recorded over the study period [*NWCC,* 2015]. The approximately 470,000 ha of burned area in Eastern Washington is almost three times the 2014 burned area, which was the next highest year. There was virtually no reburning of 2014 area; 756 ha (0.16% of 2015 burned area) burned in both years.

3.1 Climatic Drivers

Winter 2014-15 was exceptionally warm across the Pacific Northwest (although several other winters have been warmer; Figure 3). As a result, April 1 SWE was at or near record lows [*Mote et al.,* 2016], although it is worth noting that SWE has a strong effect on summer soil moisture across only part (higher elevation, mostly forested) of the domain, and summer soil moisture is also related to winter precipitation, regardless of SWE. An extremely hot summer (June-September) in 2015 led to unusually dry conditions across most of the domain.

We examined dead fuel moisture (which is affected by multiple climatic variables in combination) using 100-hour DFM for forested areas and 1-hour DFM for grasslands [*Rothermel,* 1986]. DFM values for summer 2015 were anomalously low (second-lowest in our record for both DFM measures appropriate to grassland and forest; only 2003 was lower), indicating exceptionally high fire risk (Figure 4). The 1-hour DFM anomaly (relevant to grasslands) was slightly higher (Figure 4) due to the 2015 summer temperature anomaly being higher than the precipitation anomaly; smaller fuel DFM is driven more by temperature and larger fuel by precipitation (Figure A4). Although their values differ, the 1000-hour and 10-hour DFM anomalies (not shown) are similar to the 100-hour and 1-hour DFM anomalies.

Taken over the 32-year time series, hydroclimatic variables, including summer and winter temperature, summer and winter precipitation, humidity, and 1- and 100-hour DFM, showed little correlation with burned area (Figure 3), although summer 2015 temperatures were exceptional (the warmest in the 100-year record according to the University of Washington's drought monitor) [*Mao et al.,* 2015]. The reason for low correlations among climatic variables and burned area most likely is that fire incidence is related to multiple variables, different combinations of which can lead to anomalous burned area. Climatic factors such as low DFM may not lead to fires absent the somewhat random occurrence of ignition, such as the mid-August 2015 dry lightning storm. While, on a regional scale, studies have found correlations between climatic drivers and fire incidence, the insufficiency of one indicator at a local scale is consistent with other studies that have investigated climate drivers of wildfires in both the Western US and the Pacific Northwest [*Westerling et al.,* 2006; *Stavros,* 2014; *Littell et al.,* 2009].

3.2 Non-Climatic Drivers

3.2.1 Land Cover

We evaluated land cover change to determine whether long-term trends in forest density were driving increased fire severity. In 2012, ~54% of Washington State was forested. Over our

32-year study period, 6.0% of total land area was deforested and 3.0% transitioned to forest according to Global Forest Change Database [*Hansen et al.,* 2013]. Although loss values are slightly higher than gains, we found that over 90% of the forested area at the beginning of our study period was unchanged at the end. Aside from fire damage to forests, we found no particular spatial pattern in losses or gains, or spatial relationship between land cover change and changes in burned area (Figure A2).

3.2.2 Forest Health

Given that over 50% of 2015 burned area was in forested regions (Figure 2), we considered damage to forests, primarily from Western Bark Beetles, areas as a possible factor in the extreme 2015 fire year. We examined ADS insect damage GIS Data for Washington [*USFS,* 2016]. The data showed no significant increase in forest damage between 2010-2015 and no apparent spatial relationship between damaged forest area in 2014-2015 and forest area burned in 2015. Of the area in our domain surveyed by ADS, ~5% of forest identified as "damaged" burned in 2014-2015, and a corresponding ~5% of burned area in 2014-2015 was identified as "damaged." The fraction of area damaged by beetles is not large enough to change the fuel load of forested areas as a whole.

3.2.3 Ignition

The NWCC reports that 45% of the 58 large fires (>100 acres forest or >300 acres grass/brush) across Washington in 2015 were lightning-caused. NWCC ignition data for large fires shows similar proportions of lightning-caused fires over 2005-2014. Recent years show higher percentages of area burned from lightning-caused fires, perhaps due to prioritization of firefighting in populous regions (Figure A3) [*NWCC*, 2005-2015]. Between June 1 and September 15, 2015, Oregon and Washington together had over 51,000 recorded lightning strikes, compared to a 2000-2014 average of almost 79,000 [*USDA,* 2016]. There is no indication that lightning patterns or the proportion of lightning-ignited fires were anomalously high in 2015, and no correlation between the proportion of lightning-ignited fires and burned area [*NWCC,* 2005-2015].

We did, however, find that a single cold front in mid-August played a major role in the ignition of large fires through the study area. In 2015, 80% of burned area was in fires that were first reported during the period between August 11 and 19. A large lightning storm swept the state between August 9 and 11. All of the five largest fires and 10 of the 15 largest fires began during this period [*NWCC,* 2015].

The lightning storms moved via high winds: all available weather stations in the Eastern Washington grasslands show high wind variability during August 2015, with under 5% “calm” conditions and severe gusts, particularly toward the southeast [*Agweather* 2017]. The winds drove dry lightning storms across a wide swath of Eastern Washington, leading to the ignition of multiple fires in disparate regions throughout the study area. In grasslands, the windy conditions drove rapid transmission of multiple fires before short-staffed firefighting crews were able to reach all the burns [*NWCC,* 2015].

3.2.4 Propagation and the role of cheatgrass

Because of encroaching cheatgrass (*Bromus tectorum*) across the grasslands in our domain [*Zouhar,* 2003], we investigated propagation through grassland and forests. A 2014 survey showed that the grassland portion of our study area is over 20% cheatgrass [*Herrick et al.,* 2010]. Surveys indicate that cheatgrass had reached approximately its current range of encroachment by the early 20th century, but that it has increased in density over the past 100 years [*Zouhar,* 2003]. Cheatgrass usually becomes dormant by July, and the dead grasses increase fine fuel loads during summer months [*Zouhar,* 2003, *D'Antonio and Vitousek,* 1992]. Long-term correlations between cheatgrass prevalence, fine-fuel abundance, and summertime fire frequency are well established; cheatgrass-heavy areas show evidence of depleted soil moisture and reduced prevalence of native perennial grasses [*Whisenant et al.,* 1989; *Melgoza et al.,* 1990]. Because cheatgrass is widespread in the grasslands portions of our study area, ignited grasslands in late July and August had a high fuel load. No in situ surveys of cheatgrass have been performed specifically in our domain, though, so more research is needed to verify the part it played in propagation of individual fires.

Due to the prevalence of cheatgrass across our domain, we investigated the hypothesis that early transmission via grasslands was a dominant mechanism in spread of the fires (Figure 5). We found that initial propagation through grasslands clearly occurred in several of the largest fires. Of the five largest fires in our record, three started in areas of majority grass cover and progressed into >50% forested areas, where they continued to burn in predominantly forested areas. The exception was the North Star Fire, which ignited in a completely forested area and propagated through forests; the fire was in >75% forested areas for its duration [*NWCC*, 2015].

Grassland propagation occurs rapidly, as fine fuels are consumed quickly, while forest fires burn slowly and spread widely only in combination with extreme weather conditions [*Rothermel,* 1986]. The fires that propagated early through grassland therefore likely grew in size and intensity over a short period early on. We focused on large fires because they account for a large fraction of the burned area in the region, and because smaller fires were less likely to cross the forest-grass interface. These large fires with early grassland transmission followed by longer durations in forests account for over 42% of burned area.

4 Discussion

The Western US has become increasingly vulnerable to fire during droughts [*Westerling et al.,* 2003]. Climate change predictions for the region include both increased fire activity [*Spracklen et al.,* 2009] and longer, more severe drought events [*Miles et al.,* 2007]. Our analyses show that no single factor is a strong predictor of fire vulnerability, nor was there a single major cause of the 2015 burned area anomaly. Rather, we argue that several risk factors combined to create the extreme 2015 fire season. These included exceptionally warm summer temperatures, leading to near-record low fuel moisture (for both grassland and forest), a large mid-August lightning storm, and (possibly) a continuing infestation of grasslands with non-native cheatgrass. These factors combined produce wildfires that propagated quickly (in a majority of cases, in grasslands) into dry forested regions.

Our data suggest that seasonal climate anomalies in 2015 increased fire vulnerability in two ways. First, warm temperatures in winter 2014-15 led to low spring snowpacks (despite near-normal winter precipitation) [*Mote et al.,* 2016]. The reduced snowpack expanded the spring and early summer dry period, which may have enhanced early spring growth of grass and subsequently enhanced drying of fuel loads, especially in grasslands. In addition, the longer period of warm temperatures in spring and early summer lowered DFM values during the fire season. Second, record warm temperatures during the summer of 2015 further lowered DFM by accelerating drying. The combined effect was near-record low DFM values by mid-summer.

A major cold front in mid-August accompanied by numerous dry lightning strikes across the region was responsible for many of the largest fires. All of the five largest fires were ignited during the mid-August storm. Three of them propagated initially through grassland and a fourth along the grass-forest interface, aided by high winds following passage of the front. Ultimately, over 70% of burned area in the five largest storms combined was in forests (where the fires burned more slowly but consistently given an abundance of fuel), but early transmission in grasslands played a key role in growth of the fires.

In grasslands, some studies have shown a lagging effect with the previous year's or previous season's precipitation. In extremely wet years, fine fuels can increase with augmented growing seasons. Accordingly, in the following years, fuel loads can be higher [*Littell et al.,* 2009; *Westerling et al.,* 2006]. However, the growing season for grasslands in the region primarily is winter and spring, and cheatgrass (see Section 3.2.1) in particular grows mostly during winter months [*Zouhar,* 2003]. Winter precipitation for the 2015 season was close to average (Figure 5), so it is unlikely that a lag from 2014 increased fire vulnerability.

In contrast to the role of grasslands (and possibly the role of cheatgrass) in fire propagation, the role of forest health was less apparent. Damage to forests by Western Bark Beetles did not appear to affect major portions of the forests in our domain, nor did the damaged forested areas burn any more than non-damaged regions.

5 Conclusions

Throughout the West, both the number of fires and area burned has increased over the last 30 years [*Westerling et al.,* 2006], but in Eastern Washington, 2015 was exceptional, with almost three times the area burned relative to the next highest year (2014). Our examination of a variety of potential drivers of the fires, which include physical climate variables, dead fuel moisture, land cover change, forest health, and ignition, showed only at most moderate strength of long-term relationships with burned area over a 32-year study period. We argue that rather than a single causative variable, multiple risk factors combined lead to the exceptional area burned during summer of 2015 in Eastern Washington. These include:

- Exceptionally warm summer conditions: The summer of 2015 was the warmest on record (almost 1°C warmer than the next warmest summer);
- Resulting exceptionally low dead fuel moisture in both grasslands and forests (second lowest in our 32-year study period);
- Ignition resulting from a dry lightning storm in early August. While the number of lightning strikes of the summer of 2015 was in fact somewhat below the long-term mean, the timing of the severe August 9-11 storm was critical, and that storm was responsible for igniting most of the largest fires.

Factors that may have exacerbated the extent of the fires include forest health and invasive species, particularly in the grassland portion of our domain. Though an infestation of Western Bark Beetle has affected some of the forested area of Eastern Washington, our analysis showed that the fraction of the burned area that was infested in the early stages of the larges fires was similar to that ultimately burned, suggesting no differential transmission of the fires in the infested areas. Significant parts of the grassland area (over 20%) have been infested with cheatgrass, an invasive species known to increase dead fuel loads in grasslands. There was some evidence that the largest fires were transmitted differentially in grasslands in their early stages, and cheatgrass almost certainly played some role in the rate of fire transmission. However, specific information about the location of cheatgrass in the grassland portion of the burned areas is insufficient to support a conclusion as to its effect on the area that was ultimately burned.

Figures

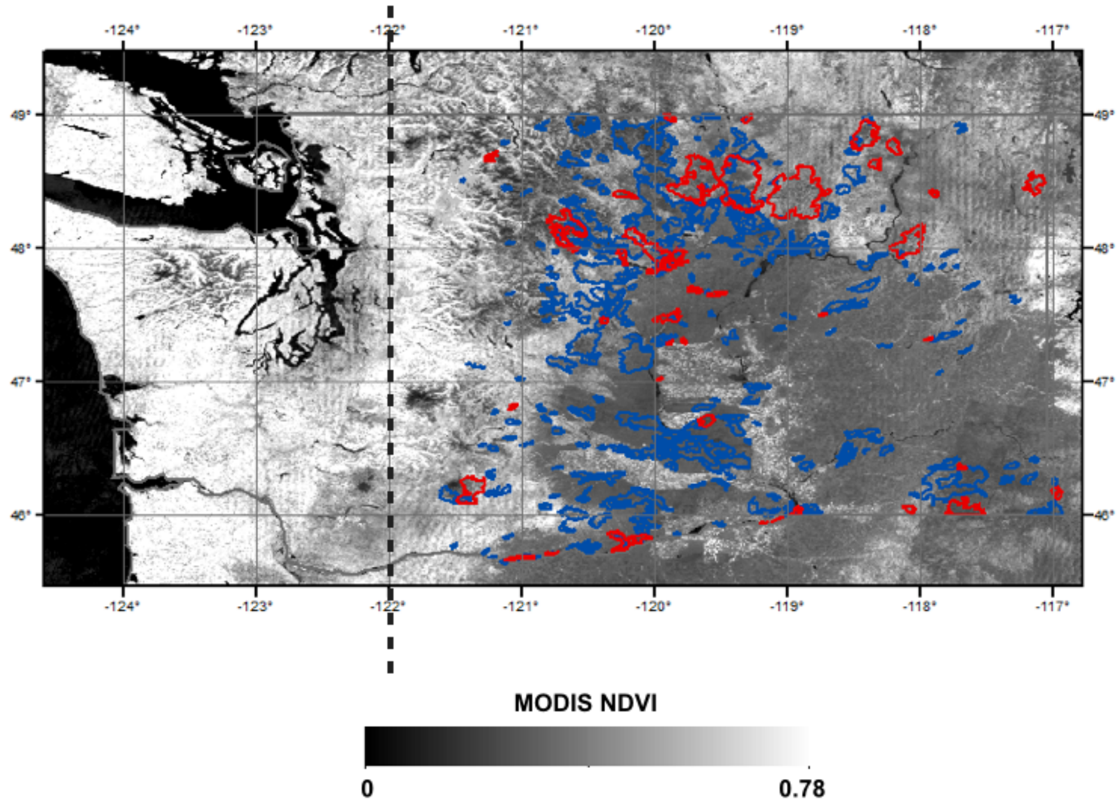

Figure 1: 2015 MODIS Normalized Difference Vegetation Index (NDVI) over Washington State (lower NDVI generally indicate grassland or urban areas, and higher NDVI generally indicate forested areas) with MTBS burned area perimeters 1984-2014 (blue) and 2015 (red). Dotted line at -122° indicates western border of study area [NDVI from *Carroll et al.,* 2004].

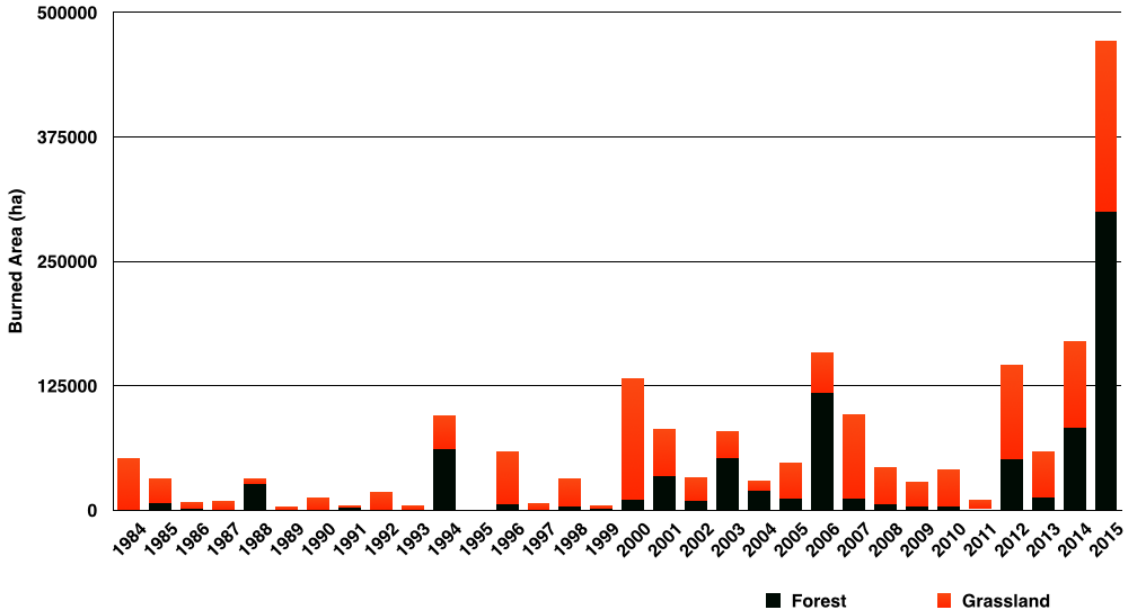

Figure 2: MTBS burned area in Eastern Washington, 1984-2015. Grassland (red), forest (black) perimeters from National Land Cover Database [*Homer,* 2011].

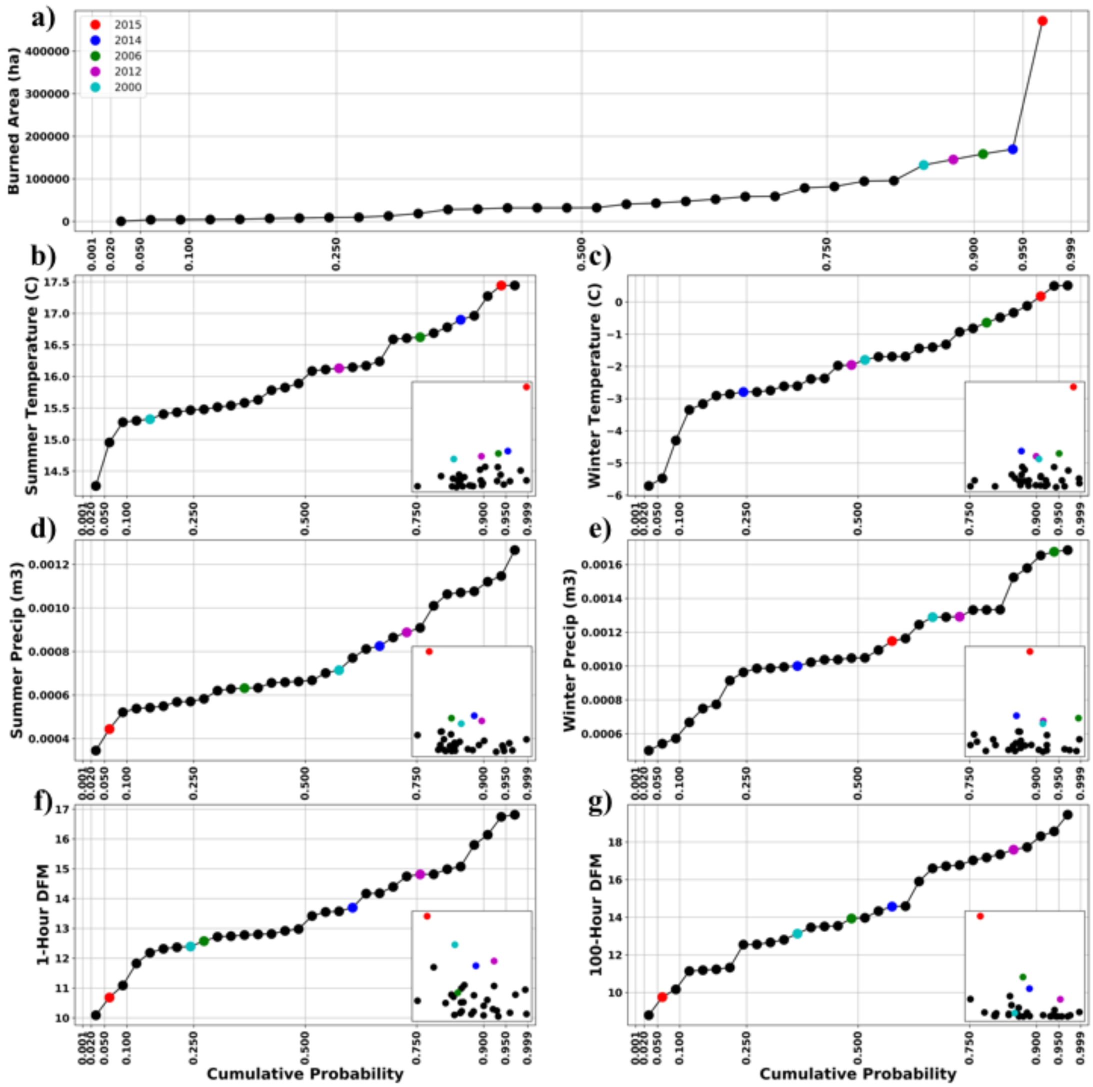

Figure 3: Cumulative distribution functions for burned area (a), summer and winter temperature (b-c), summer and winter precipitation (d-e), and 1-hour and 100-hour DFM (f-g). Inset scatterplots show individual climate variables (abscissa) and burned area (ordinate). 1-hour DFM and associated burned area computed across grasslands; 100-hour DFM and associated burned area computed across forests.

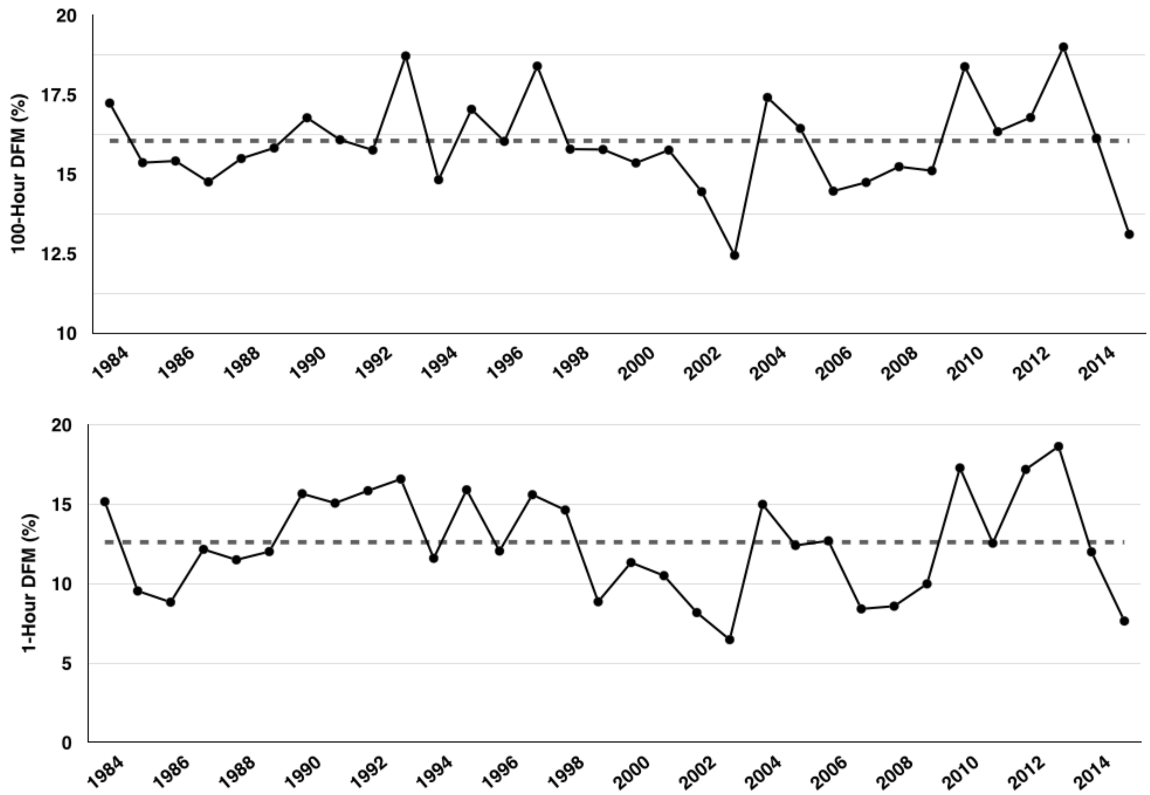

Figure 4: Dead Fuel Moisture (DFM) for Washington State. 100-hour DFM computed over forests and 1-hour DFM competed over grasslands. Dashed lines represent 32-year averages.

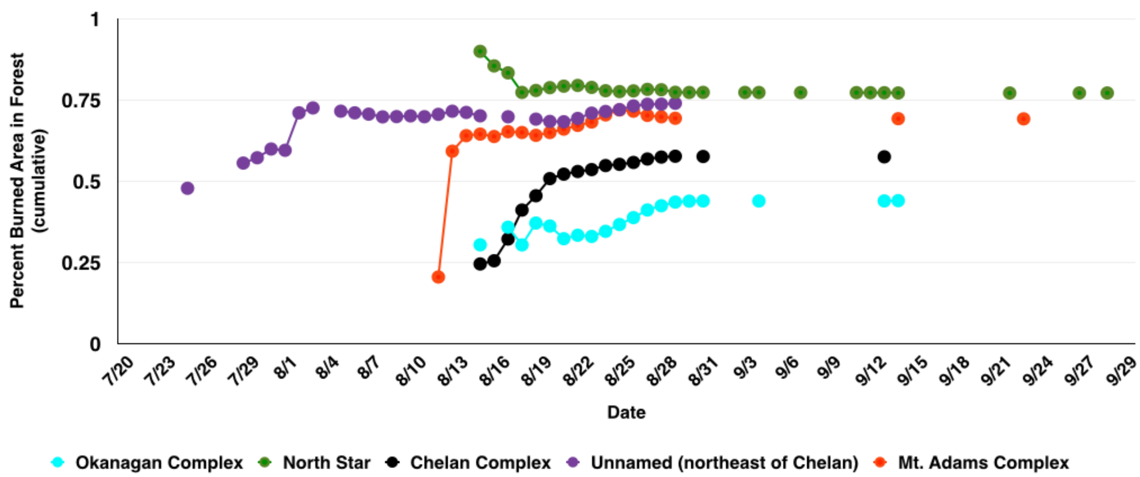

Figure 5: Propagation of FIRMS hotspots as a percentage of points in forested areas [*Homer,* 2011].

Appendix

A1 Burned area anomaly

We evaluated the MTBS burned area dataset (1984-2015) with NASA Fire Information for Resource Management System (FIRMS) active fire points (2003-2015) [*Davies et al*., 2009]. Additionally, we compared the 2015 burned area anomaly with fire perimeters from the USGS Geospatial Multi-Agency Coordination Group (GeoMAC) [*Walters et al.* 2008]. Fire data showed temporal consistency across the 32-year period of record (Figure A1). In particular, the ranking was consistent across all data sets, as was (aside from small variability) the magnitude of the 2015 anomaly. Data from the multiple data sets were also consistent spatially across our study domain.

A2 Land cover change

We examined forest change using the Global Forest Change database v1.2 [*Hansen et al.,* 2013]. We found no spatial correlation between burned area and prior forest loss (2000-2014) or forest gain (2000-2012). Clusters of forest loss reflect fires from previous years; because there was very little reburning in 2015, we did not consider forest loss in burned areas a driver of the extreme fire season (Figure A2).

A3 Ignition

We examined ignition statistics compiled by the Northwest Interagency Coordination Center (NWCC) in its annual reports. The NWCC reports classify numbers of fires and burned area by ignition source (lightning or human) within the domain of each land management agency in the region [*NWCC*, 2005-2015]. There was no apparent relationship between burned area and either percentage of lightning-caused fires or percentage of area burned from lightning-caused fires (Figure A3). The increase in recent years in percentage of area burned from lightning-caused fires could be due to prioritization of firefighting in populous areas during major fire seasons [*NWCC*, 2015]. The 2015 fire season was not anomalous in terms of ignition with respect to the historical record. Within the fire season, we did find that the timing of ignition played a role: a single cold front caused dry lightning across the state in mid-August, igniting 10 of the 15 largest fires (see Section 3.2.3).

A4 Dead Fuel Moisture

We compared Dead Fuel Moisture (DFM) climatology across our 32-year record to 2015 values. We calculated 100-hour DFM for coarse fuels in forested regions and 1-hour DFM for fine fuels in grasslands [*Cohen and Deeming*, 1985]. The 2015 DFM values are lower than climatology, signifying drier conditions and a higher fire risk (Figure A4). 1-hour DFM values are slightly more extreme because they are dependent on summer temperature, which was anomalously high in 2015. DFM values across our domain were the second-lowest in our historical record (see Section 3.1).

Appendix Figures

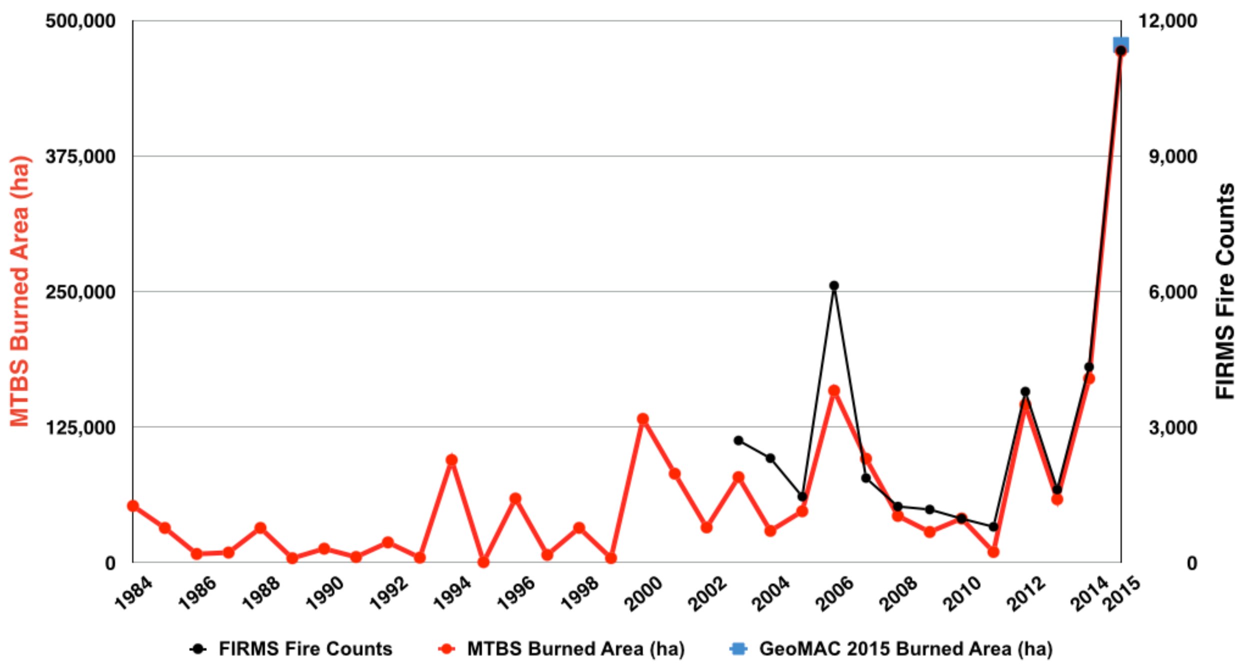

Figure A1. MTBS 1984-2015 burned area from perimeters (red), and data validation from GeoMAC 2015 burned area from perimeters (blue point, 2015 only) and 2003-2015 FIRMS fire counts (black) in Washington.

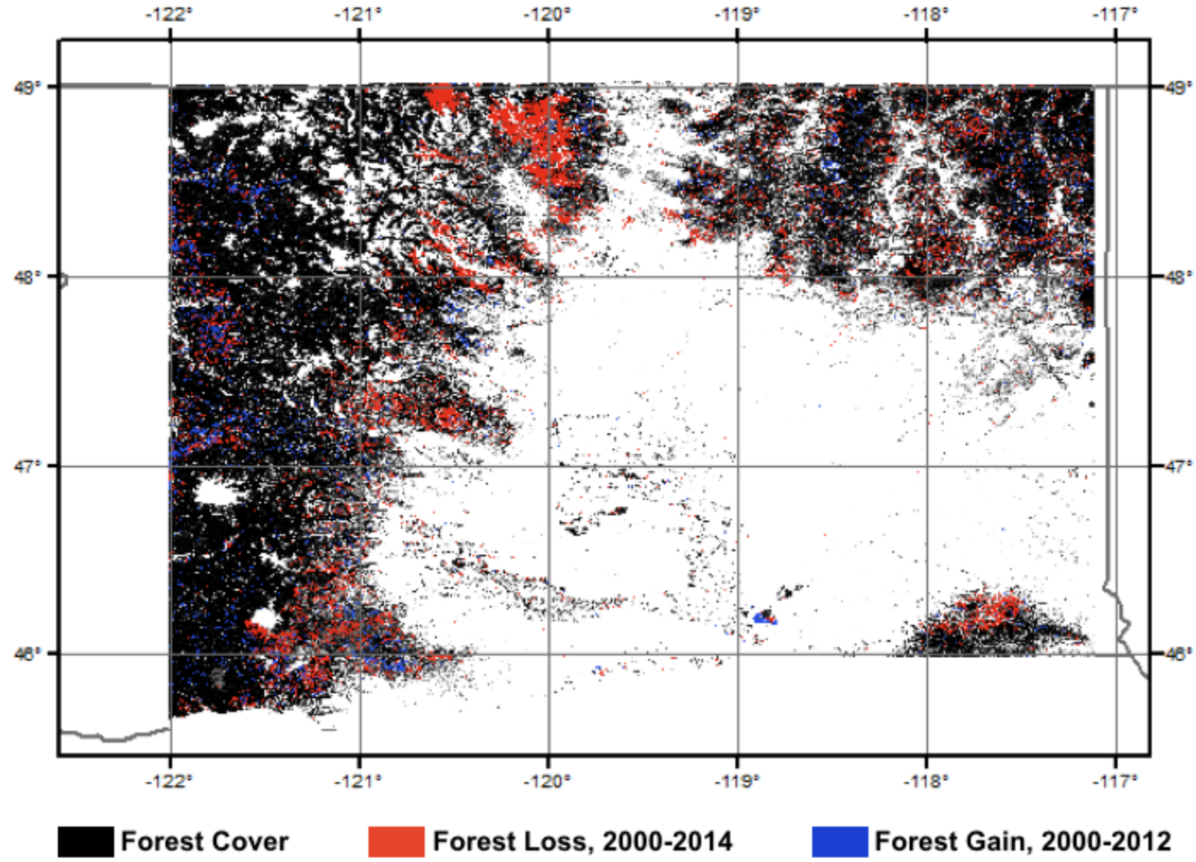

Figure A2. Global Forest Change across study domain [*Hansen et al.* 2013]. Forest cover is shown in black, Forest loss (2000-2014) in red, and forest gain (2000-2012) in blue.

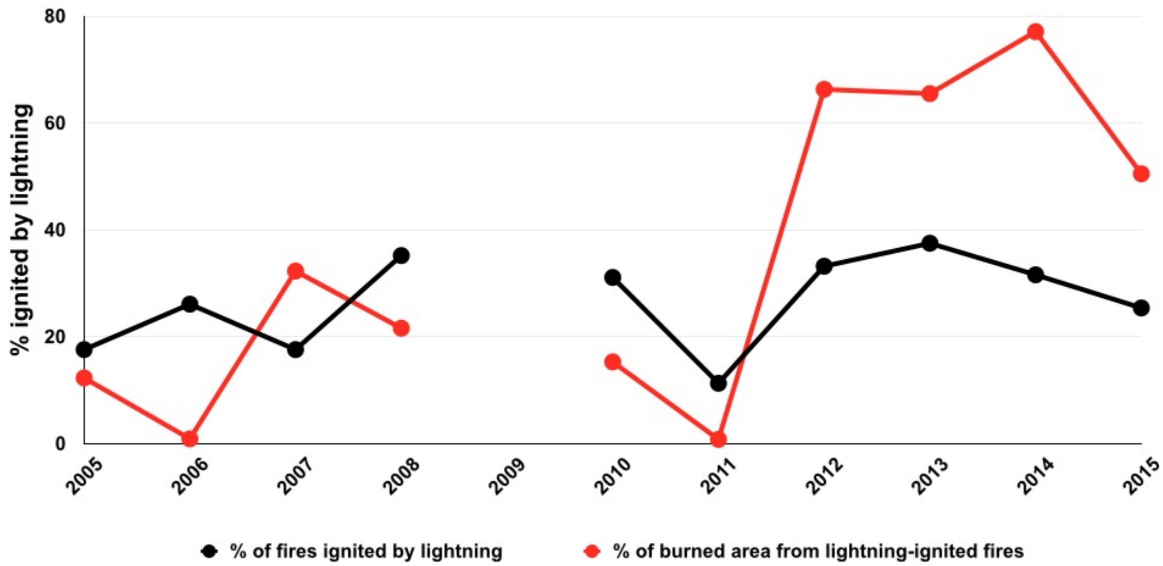

Figure A3. Percentage of lightning-ignited fires and burned area from lightning-ignited fires in Washington, 2005-2015 (data not compiled for 2009) [*NWCC,* 2005-2015].

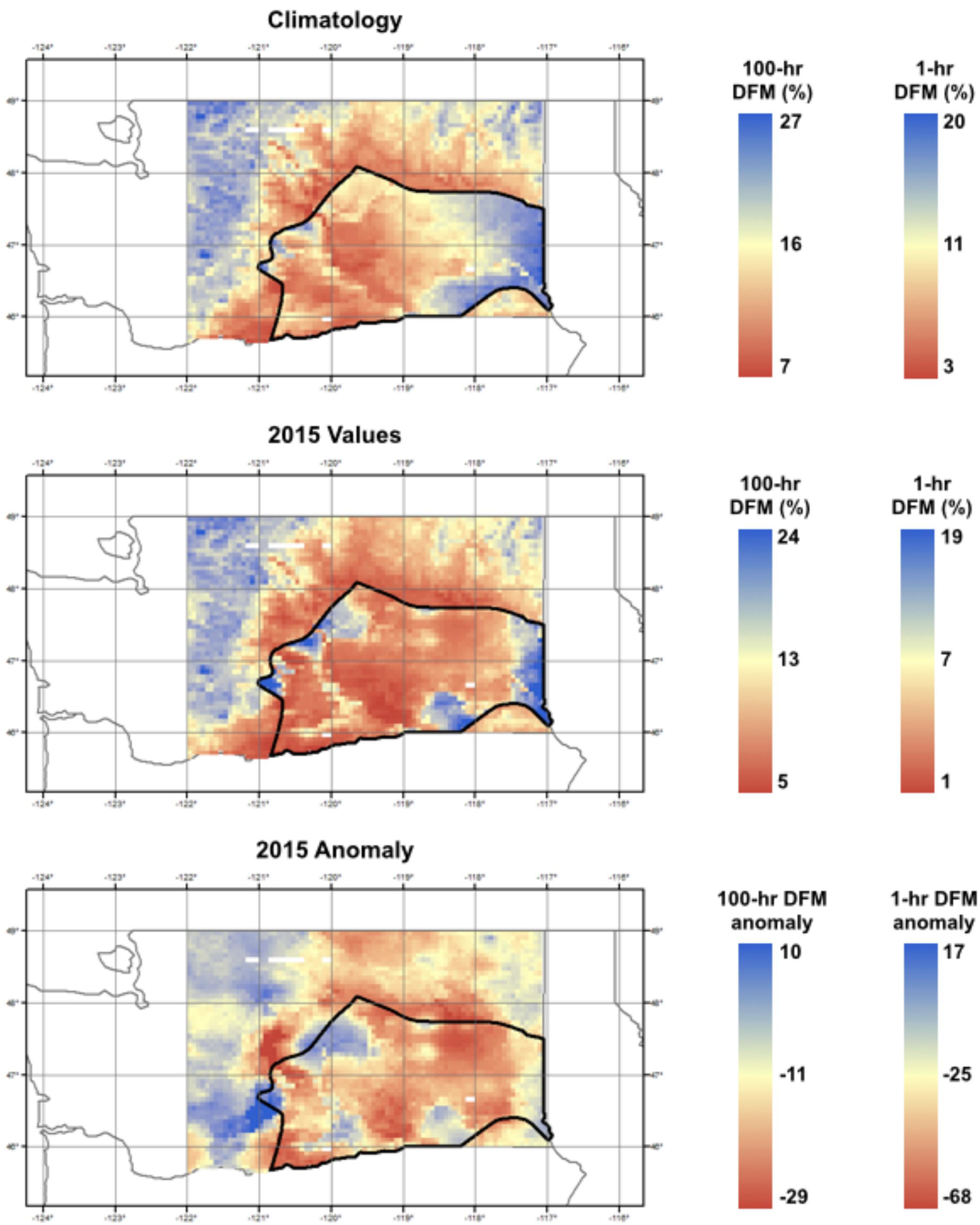

Figure A4. Dead Fuel Moisture (DFM) climatology 1984-2015, 2015 values, and normalized 2015 anomaly expressed as a percentage difference from the mean of the 32-year climatology.

100-hour DFM is shown across forests, and 1-hour DFM across grasslands. Black outline surrounds grassland in our domain.

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