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On the causes of the summer 2015 Eastern Washington wildfires

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LETTER

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Abstract

In the summer of 2015, Eastern Washington State (east of 122°W) experienced over 2000 fires that burned a record amount of area, saw the deaths of three firefighters, and caused hazardous air quality throughout much of the region. The area burned during the 2015 fire season (~471 000 hectares) was over three times that of the next largest year in the previous 32 years. We examine Eastern Washington's 2015 fire season in the context of the historical fire record, which is available from satellite remote sensing observations for the past 32 years. We explore the relationship between fire activity and physical climatic factors, including temperature and precipitation, fuel characteristics, such as dry fuel moisture, historical land cover change, forest health, and fire behavior, such as ignition and propagation. Summer 2015 was anomalously warm in Eastern Washington—nearly 1 °C warmer than the previous record warm year and 1.4 °C warmer than the 32-year climatology. It followed a near-record warm winter with anomalously low spring snowpack, whereas winter precipitation in 2014–2015 was near normal. We find that the extreme 2015 fire year was not attributable to any one physical factor, but rather was related to a combination of anomalously dry and warm summer conditions, a lightning storm in mid-August, early propagation and growth through grasslands, and high grassland fuel loadings caused by anomalous growth in the preceding late winter and spring. At the local level, prediction of the anomalous 2015 burned area is not associated with any single variable; however, the combination of conditions, especially climate and fuel loads, are likely to recur in the future.

1. Introduction

According to the National Wildfire Coordinating Committee, the summer of 2015 in the Pacific Northwest US (Washington and Oregon) was 'the most severe fire season in modern history' (Northwest Interagency Coordination Center 2015). Almost 500 000 ha in Eastern Washington (which we define as that part of Washington State east of 122 °W longitude) burned from May to September, almost five times the average over the previous 32 years (according to Monitoring Trends in Burn Severity (MTBS) data). Over 2000 fires were reported in Eastern Washington, of which over 50 were classified as large (a large fire burns more than 100 acres of forest or 300 acres of grassland, per Northwest Interagency Coordination Center 2015). Fires also contribute to air pollutant concentrations, and 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 (Northwest Interagency Coordination Center 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 2006 argue that a general warming trend and earlier spring snowmelt are associated with increased fire incidence. Fires are more common during drought conditions; historical correlations between area burned or fire occurrence and climate variables suggest that the primary drivers of anomalously high fire seasons are (lack of) precipitation and warm temperatures as well as fuel availability, wind, and humidity (Littell 2018, Westerling *et al* 2003). Land cover also plays a role; different

ecosystems have varying levels of fuel availability, which respond to antecedent precipitation and dry at different rates (Westerling *et al* 2003, Littell *et al* 2009). 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 32 years for which consistent data on the spatial extent of burns are available. In particular, we investigate the role of climate conditions associated with the anomalously warm winter of 2014–15, fuel moisture, and ignition sources. We also consider other factors, including land cover change, forest health, and early stage fire propagation, that might have played a role in the extreme fire season.

2. Methods

We focused our analysis on Eastern Washington, which had 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 122°, where the number and extent of fires were largest. This portion of Washington 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 Service, and private owners (US Geological Survey 2017).

We calculated burned area over Eastern Washington 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 MTBS database, produced by the US Geological Survey and the US Forest Service (Eidenshink *et al* 2007; <https://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 which emphasizes contrast between healthy and burned vegetation. The pre- and post-fire NBR values are compared to isolated burned area perimeters. Burned areas are further classified as wild (both natural and human-caused) 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 the remotely sensed fire perimeters are manually corrected by local experts 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 Operational Environmental Satellite (GOES) hazard mapping system. We compared MTBS burned area with FIRMS points and GeoMAC area across the Pacific Northwest (figure S1 is available online at stacks.iop.org/ERC/1/011009/mmedia), and found that, visually, the three 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 S1).

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 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). Other studies have used 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 that may affect fire vulnerability, we used the USFS Dead Fuel Moisture (DFM) content (Cohen and Deeming 1985).

Following Gergel *et al* 2017, we calculated DFM at a 1/16° 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 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-h time lags for grassland areas, which are applicable to fuel under 1 inch in diameter, and 100- and 1000-h time lags for forested areas, for fuel sizes of 1–8 inches in diameter (Brown *et al* 2004). The 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 US 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).

To evaluate growing season and multi-year cycles, we used Landsat 7 Normalized Difference Vegetation Index (NDVI) 8-day composite images at a 30 m resolution (Chandler *et al* 2009) from 2000–2015. We examined seasonal NDVI averages for summer (JJA), winter (DJF), and spring (MAM) to understand changes in fuel load and to see whether there was any evidence of lagged effects (multi-year drought) that might have impacted DFM values.

2.3. Non-climatic drivers

2.3.1. Land cover

Because fire regimes can be altered by vegetation, we evaluated changes in land cover over our 32-year period of record. 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 *et al* 2012). We examined MTBS polygons across land cover classes to compare forested and grassland burned area. Additionally, we classified FIRMS active fire points by land cover class to evaluate fire propagation across forests and grasslands. We relied on the 2011 NLCD because of its high spatial resolution and because forest-grassland interfaces did not change substantially over the study period, despite forest loss from fires in previous years (figure S2). Grassland in our study area is primarily a mix of short shrub/scrubland (52%), hay and cropland (36%), and grass (11%) (Homer *et al* 2012). We refer to this mix of fast-burning low vegetation cover as 'grassland' to differentiate it from forest, but we note its heterogeneity. In particular, areas near the forest interface are more likely to be scrubland than the interior of the grassland region shown in figure 1. Because the relative sizes of land cover classes did not change during our study period, we argue that the forest-grassland interface was relatively stable over our period of analysis as well (Watson *et al* 2000).

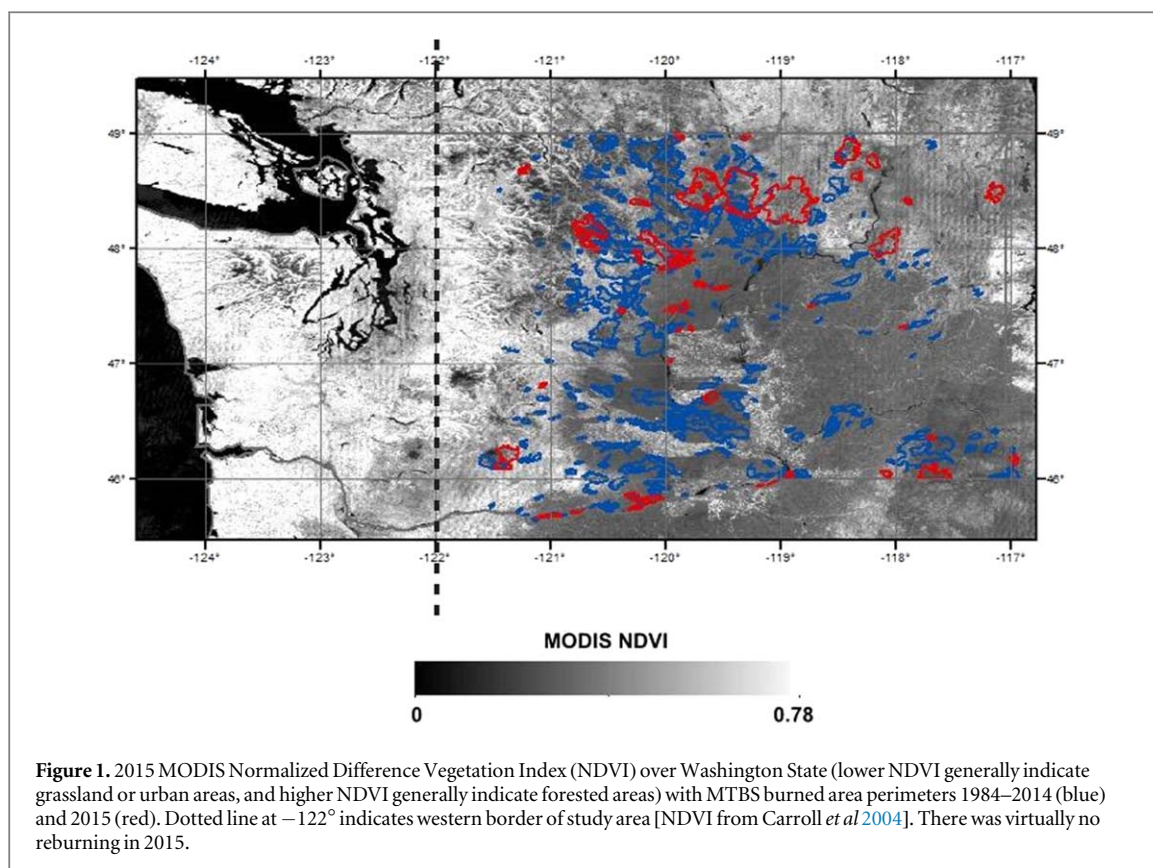
To verify consistency in land cover, we examined forest change across our domain using the Global Forest Change database v1.2 (Hansen *et al* 2013), which compares Earth observation satellite images (primarily from Landsat) over time to measure forest cover losses from 2000–2014 and forest cover gains from 2000–2012. Forest loss data are available through 2015, but almost exclusively reflect the summer fire season. Accordingly, we limited forest change analysis through 2014. As of this writing, the forest loss data end in 2012. While different forests with varied fire histories respond differently to moisture change, for the purposes of this study we considered forests to be essentially homogenous and, on this basis, we examined changes in recent forest cover and health.

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 (US Forest Service 2016). ADS surveys cover the forested areas of our domain. They are conducted by local experts, who observe forest damage from a high-winged aircraft and record specific damage sites on a map. Flyovers in Washington have been conducted annually (1947–2016), and forest damage is recorded at a quarter-tree scale (US Forest Service 2016). Because ADS surveys do not include flights over actively burning areas, and therefore the 2015 data are incomplete in our region of study, 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. Sources of ignition

Because no quantitative data on long-term ignition trends across our study domain were available, we drew on ignition data (2012–2015) from the Northwest Interagency Coordination Center (NWCC) annual reports. NWCC reports all fires in Oregon and Washington, gives their total area burned, and assigns ignition as human, lightning, or undetermined. We evaluated burned area and fire counts with respect to ignition sources, and applied NWCC data to MTBS burned area maps and NWCC fire incident data to examine spatial and temporal ignition trends within the 2015 fire season.



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 produce 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 (figure S3).

3. Results

The summer 2015 burned area clearly was exceptional relative to our study period –6.8 times the 1984–2015 mean and 14.6 times the 1984–2015 median (figure 2). Summer 2015 also had the highest fire counts in the study period (figure S1). The Okanogan Complex Fire, which dominated the northern forested part of the domain, was the largest individual fire recorded over the study period ($\sim 120\,000$ ha) (Northwest Interagency Coordination Center 2015). The approximately 500 000 ha of burned area in Eastern Washington is almost three times the 2014 burned area, which was the next highest year. There was hardly any re-burning of 2014 area; 756 ha (0.16% of 2015 burned area) burned in both years.

3.1. Climatic drivers

3.1.1. Dead fuel moisture

Winter 2014–15 was exceptionally warm across the Pacific Northwest (although several other winters have been warmer across both the 32- and 100-year records; figure 3). As a result, April 1 (end-of-winter) Snow Water Equivalent (SWE) was at or near record lows (Mote *et al* 2016). We note that SWE has a strong effect on summer soil moisture across only part (higher elevation, mostly forested) of the domain, and that summer soil moisture is related to winter precipitation, regardless of SWE. An extremely hot summer (June–September) in 2015 led to unusually dry summer conditions across most of the domain.

We examined dead fuel moisture (which is affected by multiple climatic variables in combination) using 100-h DFM for forested areas and 1-h DFM for grasslands (Rothermel *et al* 1986). Smaller fuel DFM is driven more by temperature and larger fuel by precipitation. DFM values for summer 2015 were anomalously low (second-lowest in our record for both DFM measures; only 2003 was lower), indicating exceptionally high fire risk (figure 4). The 1-h DFM anomaly (relevant to grasslands) was slightly higher (figure 4) due to the 2015

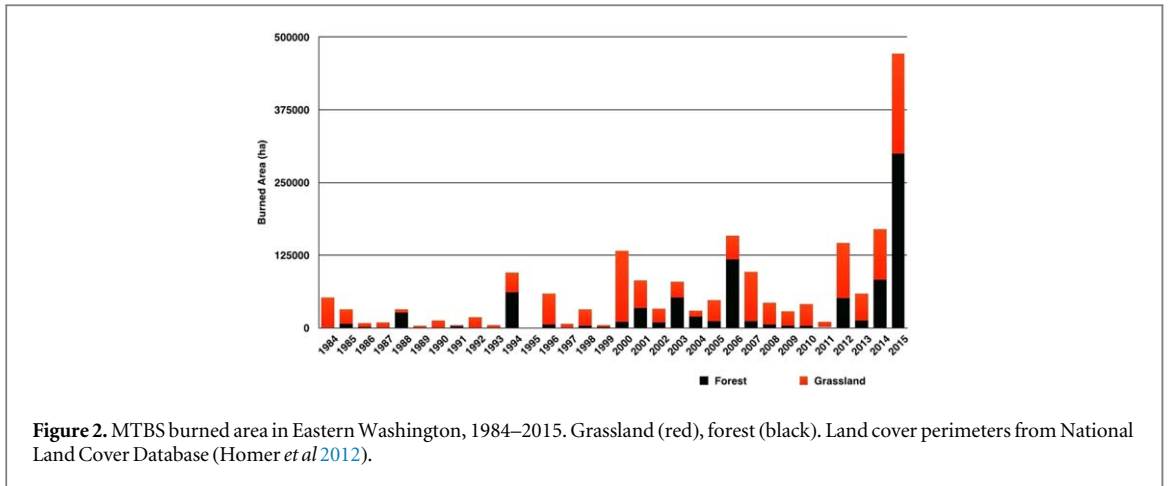


Figure 2. MTBS burned area in Eastern Washington, 1984–2015. Grassland (red), forest (black). Land cover perimeters from National Land Cover Database (Homer *et al* 2012).

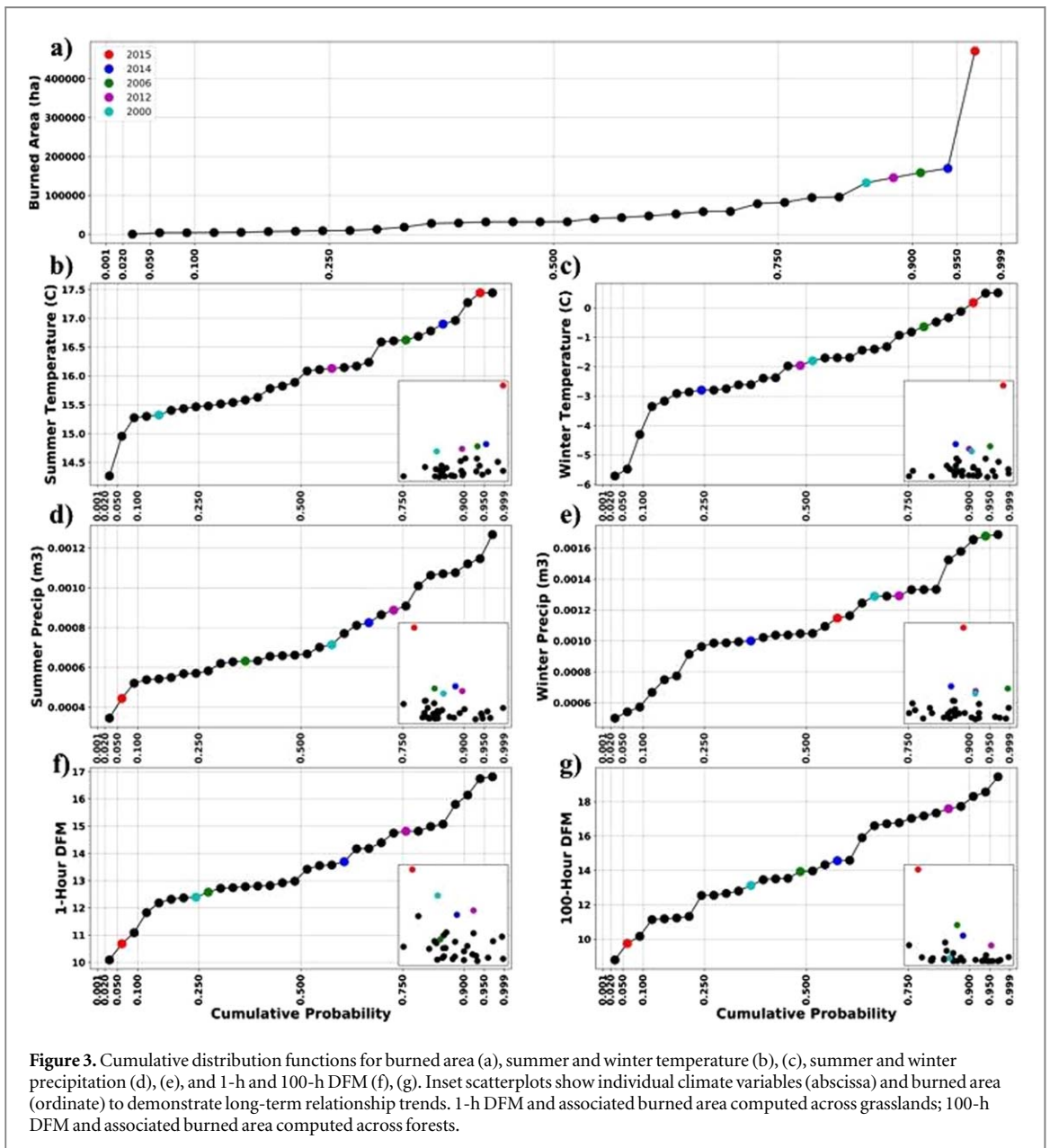
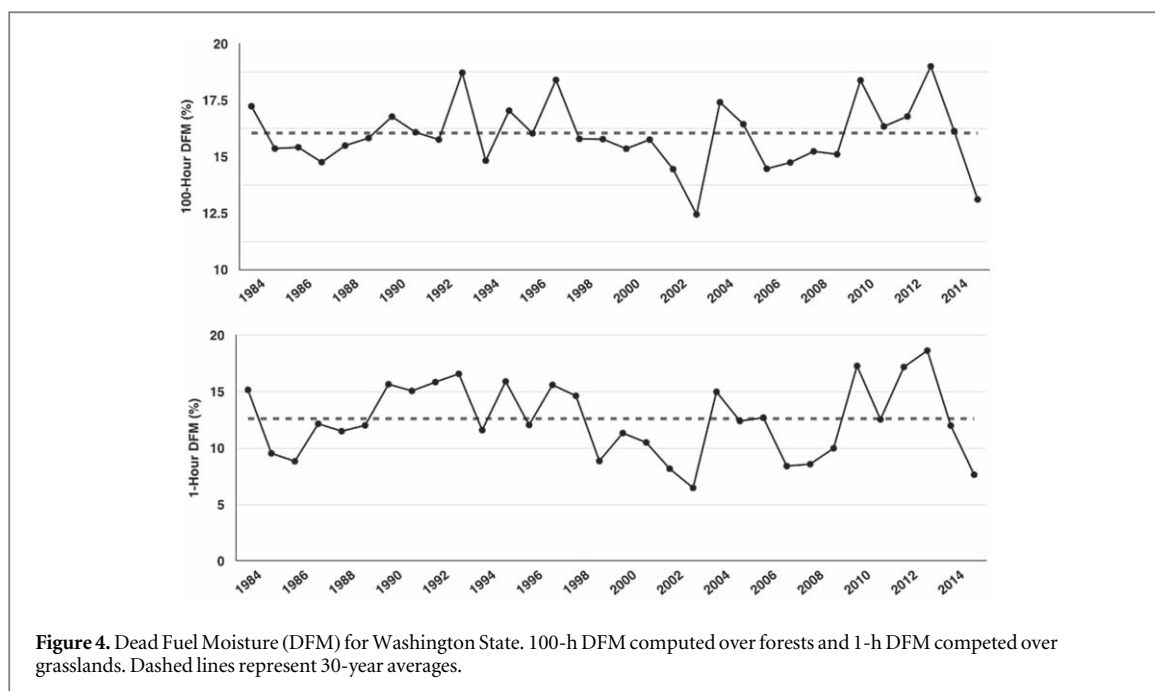


Figure 3. Cumulative distribution functions for burned area (a), summer and winter temperature (b), (c), summer and winter precipitation (d), (e), and 1-h and 100-h DFM (f), (g). Inset scatterplots show individual climate variables (abscissa) and burned area (ordinate) to demonstrate long-term relationship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



summer temperature anomaly being higher than the precipitation anomaly (figure S5). Although their values differ, the 1000-h and 10-h DFM anomalies (not shown) are similar to the 100-h and 1-h DFM anomalies.

3.1.2. Multi-year drought

We examined seasonal climatology across 2014–2015 for evidence of multi-year drought effects. Summer (JJA) 2014 and winter (DJF) 2015 precipitation were above average across our 32-year record (figure 3). High temperatures from summer 2014 through summer 2015 were not sufficient to establish extended drought; rather they led to early snowmelt and an extended dry season that was limited to summer 2015. Winter NDVI in 2015 was the highest in a 16-year record (figure S6(a)), indicating that conditions were sufficiently wet for substantial vegetation growth to occur (see below).

Additionally, a multi-year effect would potentially drive increased fire risk in 2016. However, 2016 had fewer than 119 000 ha burned in our study area—about average for the 32-year record despite ‘above-average fire danger’ early in the season and from mid-July through September (Northwest Interagency Coordination Center 2016).

3.1.3. Fuel load

We considered the role of high fuel loads in the exceptional 2015 fire season. Winter and spring of 2015 had the highest and second-highest NDVI values respectively over the (relatively short) 2000–2015 record (figure S6(a)). Despite average spring soil moisture, the warm 2015 winter, normal precipitation, and subsequent early snowmelt led to an earlier growing season and increased fine fuels (figure S6(b)). Spring NDVI values in 2013–2014 were also high (the third and fourth highest values on record), and the strong multi-year growth may have further increased the overall fuel load at the onset of the 2015 fire season. In particular, the high NDVI values may have increased 2015 live fuels, adding to the fuel load of coniferous forests. Live fuel moisture content is either measured directly (most cases) or estimated using algorithms based on vegetation type, climate zone, and temperature (Burgan 1979). Other estimators use soil moisture and temperature or remotely sensed greenness (e.g. NDVI, NDWI) (Qi *et al* 2012). Because the factors that influence dead and live fuel moisture anomalies are positively correlated—both approximate factors that control drying—it is highly likely that live fuels were anomalous in 2015, as were DFM anomalies, which we computed (Rossa and Fernandez 2018).

3.2. Non-climatic drivers

3.2.1. Land cover

We evaluated land cover change to determine whether long-term trends in forest density or grassland composition drove 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 about

90% of the forested area at the beginning of our study period was unchanged at the end, though changes to forest density might have occurred within forested regions. 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 S2).

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 Spruce Bark Beetles and Mountain Pine Beetles, areas as a possible factor in the extreme 2015 fire year. Mortality from beetle damage can cause increased fire risk the following year (Jenkins *et al* 2008).

To understand whether forest health has changed in recent years, we examined ADS insect damage GIS Data for Washington (US Forest Service 2016). The data showed that no significant increase in forest damage occurred between 2010–2015, and that there was 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. Recent research has shown that, over a 25-year record, insect damage has no correlation to burned area, and in fact may have a dampening effect on fire severity (Meigs *et al* 2015, 2016).

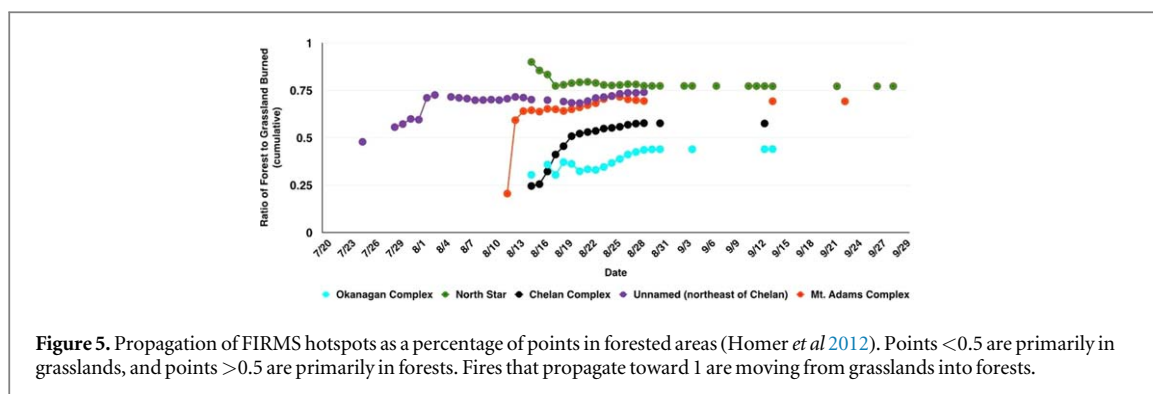
3.2.3. Ignition

Records show that, in our study region, lightning was responsible for more than half of the wildfires between 1992–2012 (Balch *et al* 2017). The NWCC reports that 45% of the 58 large fires across Washington in 2015 were lightning-caused. NWCC ignition data for large fires show similar proportions of lightning-caused fires over 2005–2014. Recent years have somewhat higher percentages of area burned from lightning-caused fires (figure S4), perhaps due to prioritization of firefighting in populous regions (Northwest Interagency Coordination Center 2005–2015). Between June 1 and September 15, 2015, Oregon and Washington together had over 510 00 recorded lightning strikes, compared to a 2000–2014 average of almost 790 00 (US Department of Agriculture 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 (section S4) (Northwest Interagency Coordination Center 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 in our study region during 2015 began during this period (Northwest Interagency Coordination Center 2015). The number of fires started during this week also led to swift propagation of many fires, as firefighting crews did not have the resources to immediately suppress all the fires (Northwest Interagency Coordination Center 2015).

3.2.4. Propagation

There were anecdotal reports of early stage transmission of some of the large fires through grasslands, and particularly areas infested with cheatgrass (*Bromus tectorum* L. (Poaceae)) an invasive species that is highly flammable in summer and is pervasive (albeit spotty) across much of Eastern Washington (Zouhar 2003). We therefore investigated propagation of the largest fires through grassland and forests. We focused on large fires (figure S7) 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. We found that initial propagation through grasslands clearly occurred in several of the largest fires. Of the five largest fires in 2015, three started in areas of majority grass cover and progressed into >50% forested areas, where they continued to burn in predominantly forested areas (figure 5). The exception was the North Star Fire (shown in green), which ignited in a completely forested area and propagated through forests; the fire was in >75% forested areas for its duration. 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 *et al* 1986). The fires that propagated early through grassland therefore likely grew in size and intensity over a short period early on, and developed through wooded areas (regions with scrub or sparse tree cover) that exist across the forest-grassland interface and into denser forests (Watson *et al* 2000). These large fires with early grassland transmission followed by longer durations in forests account for over 42% of burned area.



4. Discussion

Although the 2015 fire season in Eastern Washington was highly anomalous, our analyses show that there was no single cause. Rather, we argue that several risk factors combined to create the extreme 2015 fire season. These include exceptionally warm summer temperatures, which led to near-record low fuel moisture (for both grassland and forest), a large lightning storm in August, and rapid propagation of large fires (mostly) across grasslands (which had enhanced biomass due to two previous years of enhanced spring growth) and (mostly) into dry forested regions.

Our data suggest that seasonal climate anomalies in 2015 increased fire hazard 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 enhanced early springtime grass growth and subsequently extended the drying period for fuel loads. 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.

Taken over the 32-year time series, hydroclimatic variables including summer and winter temperature, summer and winter precipitation, and 1- and 100-h DFM, showed little correlation with burned area (figure 3 insets). However, summer 2015 temperatures were the warmest in a 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, even when combined into a more comprehensive metric such as DFM, may not lead to fires absent the somewhat random occurrence of ignition, such as the early August 2015 dry lightning storm. While, on a regional scale, some studies have found correlations between climatic drivers and fire incidence (Westerling 2006), 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 (Stavros *et al* 2014, Littell *et al* 2009). Increased spring NDVI demonstrates a likely increase in live fuels, a metric that has become more commonplace at a larger regional scale (Abatzoglou and Kolden 2013, Littell 2018). However, fuel is still an insufficient single indicator for burned area.

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, where fuel loads were high, 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 drove the rapid growth of the fires.

In contrast to the role of grasslands 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 as surveyed by the US Forest Service.

5. Conclusions

Throughout the West, both the number of fires and area burned has increased over the last 30 years (Dennison *et al* 2014). In Eastern Washington, the fire season of 2015 was exceptional even in this context. Our examination of a variety of potential drivers of the fires showed only moderate long-term correlations of any candidate predictors with burned area over a 32-year study period. Rather than a single causative variable, multiple risk

factors appeared to lead to the exceptional area burned during summer 2015 in Eastern Washington. Exceptionally warm summer conditions which led to very low dry fuel moisture levels, ignition of most of the largest fires during a dry lightning storm in early August, and possibly enhanced growth of fine fuels during the spring of 2015 following a low winter snowpack, and similar enhanced growth the year before.

At a local level, the number of disparate risk factors involved in producing a severe fire season complicates long-term trend analysis and predictions. Nonetheless, the low DFM values that accompanied the record high summer temperatures in 2015 are a risk factor that seems likely to recur with greater frequency as the climate continues to warm (Litell 2018). Another risk factor that appeared to be present in 2015 was high fine fuel loadings, which may have been related in part to the extended spring growing season associated with early melt of an anomalously low winter 2014–15 snowpack and accordingly high winter and spring NDVI (figure S6(a)), as well as buildup from high spring 2013 and 2014 NDVI. The climate conditions that lead to the fine fuel anomaly likewise are likely to recur with greater frequency in a warming climate.

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References

- Abatzoglou J T and Kolden C A 2013 Relationships between climate and macroscale area burned in the western United States *Int. J. Wildland Fire* **22** 1003–20
- Balch J K *et al* 2017 Human-started wildfires expand the fire niche across the United States *Proc. Natl Acad. Sci.* **114** 2946–51
- Bohn T J, Livneh B, Oyster J W, Running S W, Nijssen B and Lettenmaier D P 2013 Global evaluation of MTCLIM and related algorithms for forcing of ecological and hydrological models *Agric. For. Meteorol.* **176** 38–49
- Brown T J, Hall B L and Westerling A L 2004 The impact of twenty-first century climate change on wildland fire danger in the western United States: an applications perspective *Clim. Change* **62** 365–88
- Burgan R E 1979 *Estimating Live Fuel Moisture for the 1978 National Fire Danger Rating System* (Ft Collins, CO: Forest Service, US Department of Agriculture, Intermountain Forest and Range Experiment Station)
- Carroll M L, DiMiceli C M, Sohlberg R A and Townshend J R G 2004 *250m MODIS Normalized Difference Vegetation Index Collection 4* (College Park, MD: University of Maryland)
- Chandler G, Markham B L and Helder D L 2009 Summary of current radiometric calibration coefficients for Landsat MSS *Remote Sens. Environ.* **113** (5) 893–903
- Cohen J D and Deeming J E 10.2737/PSW-GTR-82 1985 *The National Fire-Danger Rating System: Basic Equations* (Berkeley, CA: Gen Tech Rep PSW-82)
- Davies D K, Ilavajhala S, Wong M M and Justice C O 2009 Fire information for resource management system: archiving and distributing modis active fire data *IEEE Trans. Geosci. Remote Sens.* **47** 72–9
- Dennison P E *et al* 2014 Large wildfire trends in the western United States, 1984–2011 *Geophys. Res. Lett.* **41** 2928–33
- Eidenshink J, Schwind B, Brewer K, Zhu Z, Quayle B and Howard S 2007 A project for monitoring trends in burn severity *Fire Ecology* **3** (1) 3–21
- Gergel D R, Nijssen B, Abatzoglou J T, Lettenmaier D P and Stumbaugh M R 2017 Effects of climate change on snowpack and fire potential in the western USA *Clim. Change* **141** 287–99
- Hansen M C *et al* 2013 High-resolution global maps of 21st-century forest cover change *Science* **342** 850–3
- Homer C H, Fry J A and Barnes C A 2012 The National Land Cover Database *US Geological Survey Fact Sheet* **3020** 1–4
- Jenkins M J, Hebertson E, Page W and Jorgensen C A 2008 Bark beetles, fuels, fires and implications for forest management in the Intermountain West *Forest Ecol. Manage.* **254** 16–34
- Litell J S 2018 Drought and fire in the western USA: is climate attribution enough? *Current Climate Change Reports* **4** 396–406
- Littell J S, McKenzie D, Peterson D L and Westerling A L 2009 Climate and wildfire area burned in western US ecoprovinces, 1916–2003 *Ecological Applications* **19** 1003–21
- Littell J S, Oneil E E, McKenzie D, Hicke J A, Lutz J A, Norheim R A and Elsner M M 2010 Forest ecosystems, disturbance, and climatic change in Washington State, USA *Clim. Change* **102** 129–58
- Livneh B, Bohn T J, Pierce D W, Munoz-Arriola F, Nijssen B, Vose R, Cayan D R and Brekke L 2015 A spatially comprehensive, hydrometeorological data set for Mexico, the US, and Southern Canada 1950–2013 *Sci. Data* **2** 150042
- Livneh B, Rosenberg E A, Lin C, Nijssen B, Mishra V, Andreadis K M, Maurer E P and Lettenmaier D P 2013 A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States: update and extensions *J. Climate* **26** 9384–92
- Mao Y, Nijssen B and Lettenmaier D P 2015 Is climate change implicated in the 2013–2014 California drought? A hydrologic perspective *Geophys. Res. Lett.* **42** 2805–13
- Marlier M E, Xiao M, Engel R, Livneh B, Abatzoglou J T and Lettenmaier D P 2017 The 2015 drought in Washington State: a harbinger of things to come? *Environ. Res. Lett.* **12** 114008

- Meigs G W, Zald H S J, Campbell J L, Keeton W S and Kennedy R E 2016 Do insect outbreaks reduce the severity of subsequent forest fires? *Environ. Res. Lett.* **11** (4)
- Mote P W, Hamlet A F, Clark M P and Lettenmaier D P 2005 Declining mountain snowpack in Western North America *Bull. Amer. Meteor. Soc.* **86** 39–49
- Mote P W, Rupp D E, Li S, Sharp D J, Otto F, Uhe P F, Xiao M, Lettenmaier D P, Cullen H and Allen M R 2016 Perspectives on the causes of exceptionally low 2015 snowpack in the western United States *Geophys. Res. Lett.* **43** 10980–988
- NWCC Predictive Services Unit: Intelligence Section 2005 *Northwest Annual Fire Report*. Northwest Interagency Coordination Center
- NWCC Predictive Services Unit: Intelligence Section 2006 *Northwest Annual Fire Report*. Northwest Interagency Coordination Center
- NWCC Predictive Services Unit: Intelligence Section 2007 *Northwest Annual Fire Report*. Northwest Interagency Coordination Center
- NWCC Predictive Services Unit: Intelligence Section 2008 *Northwest Annual Fire Report*. Northwest Interagency Coordination Center
- NWCC Predictive Services Unit: Intelligence Section 2010 *Northwest Annual Fire Report*. Northwest Interagency Coordination Center
- NWCC Predictive Services Unit: Intelligence Section 2011 *Northwest Annual Fire Report*. Northwest Interagency Coordination Center
- NWCC Predictive Services Unit: Intelligence Section 2012 *Northwest Annual Fire Report*. Northwest Interagency Coordination Center
- NWCC Predictive Services Unit: Intelligence Section 2013 *Northwest Annual Fire Report*. Northwest Interagency Coordination Center
- NWCC Predictive Services Unit: Intelligence Section 2014 *Northwest Annual Fire Report*. Northwest Interagency Coordination Center
- NWCC Predictive Services Unit: Intelligence Section 2015 *Northwest Annual Fire Report*. Northwest Interagency Coordination Center
- NWCC Predictive Services Unit: Intelligence Section 2016 *Northwest Annual Fire Report*. Northwest Interagency Coordination Center
- Qi Y, Dennison P E, Spencer J and Riano D 2012 Monitoring live fuel moisture using soil moisture and remote sensing proxies *Fire Ecology* **8** (3) 71–87
- Rossa C G and Fernandes P M 2018 On the effect of live fuel moisture content on fire-spread rate *Forest Systems* **26** 8
- Rothermel R C, Wilson R A, Morris G A and Sackett S S 1986 Modeling moisture content of fine dead wildland fuels: input to the BEHAVE fire prediction system *Research Paper INT-359* Vol 359 (Ogden, UT: US Department of Agriculture, Forest Service, Intermountain Research Station) 61
- Stavros E N, Abatzoglou J T, Larkin N K, McKenzie D and Steel E A 2014 Climate and very large wildland fires in the contiguous western USA *Int. J. Wildland Fire* **23** 899
- US Department of Agriculture 2016 *Narrative timeline of the Pacific Northwest 2015 fire season*. (Portland, OR: US Department of Agriculture)
- US Forest Service 2016 *Aerial Insect and Disease Survey GIS Data for Oregon and Washington 1947–Present*. Washington department of natural resources and Oregon department of forestry
- US Geological Survey 2017 *The National Map: Federal Lands and Indian Reservations*. US Department of the Interior
- Walters S P, Schneider N J and Guthrie J D 2008 Geospatial Multi-Agency Coordination (GeoMAC) Wildland Fire Perimeters *US Geological Survey Data Series* **612** 6
- Watson R T, Noble I R, Bolin B, Ravindranath N H, Verardo D J and Dokken D J (ed) 2000 *Land Use, Land-Use Change, and forestry—A Special Report of the Intergovernmental Panel on Climate Change (IPCC)* (Cambridge: Cambridge University Press) 377
- Westerling A L 2006 Warming and earlier spring increase western US forest wildfire activity *Science* **313** 940–3
- Westerling A L, Gershunov A, Brown T J, Cayan D R and Dettinger M D 2003 Climate and Wildfire in the Western United States *B. Am. Meteorol. Soc.* **84** 595–604
- Zouhar K 2003 *Bromus tectorum Fire Effects Information System* (Ft Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer)) [Online]