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Predicting increasing high severity area burned for three forested regions in the western United States using extreme value theory

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ABSTRACT

More than 70 years of fire suppression by federal land management agencies has interrupted fire regimes in much of the western United States. The result of missed fire cycles is a buildup of both surface and canopy fuels in many forest ecosystems, increasing the risk of severe fire. The frequency and size of fires has increased in recent decades, as has the area burned with high severity in some ecosystems. A number of studies have examined controls on high severity fire occurrence, but none have yet determined what controls the extent of high severity fire. We developed statistical models predicting high severity area burned for the western United States and three sub-regions—the Northern Rocky Mountains, Sierra Nevada Mountains, and Southwest. A simple model with maximum temperature the month of fire, annual normalized moisture deficit and location explains area burned in high severity fire in our west-wide model, with the exception of years with especially large areas burned with high severity fire: 1988, 2002. With respect to mitigation or management of high severity fire, understanding what drives extreme fire years is critical. For the sub-regional models, topography, spring temperature and snowpack condition, and vegetation condition class variables improved our prediction of high severity burned area in extreme fire years. Fire year climate is critical to predicting area burned in high severity fire, especially in extreme fire years. These models can be used for scenario analyses and impact assessments to aid management in mitigating negative impacts of high severity fire.

1. Introduction

More than 70 years of fire suppression by federal land management agencies has interrupted fire regimes in parts of the western United States (US). Many forest types that historically burned frequently have undergone significant changes in species composition and have heavy accumulations of surface and canopy fuels, putting them at risk for severe fires (Agee et al., 1978; Agee and Skinner, 2005; McKelvey et al., 1996; Keane et al., 2002). Of ∼168 million hectares of fire adapted ecosystems in the coterminous US, more than 29 million are considered high risk to human and ecosystem values due to an accumulation of fuels and risk of high severity fire, and more than 57 million are considered a moderate risk (Cleaves, 2001). A high severity fire is exemplified by a stand replacing fire where most surface and crown fuels are burned and most over-story vegetation is killed.

Both the frequency and size of large wildfires have increased in the past 30 years in the western US (Dennison et al., 2014; Littell et al., 2009; Miller et al., 2009; Stephens and Ruth, 2005; Westerling et al., 2006; Westerling, 2016) as has the length of the fire season (Westerling et al., 2006; Jolly et al., 2015; Westerling, 2016). Climate affects area burned through both production of biomass and fuels, enhanced after wet winters and springs, and the drying of fuels, enhanced by drought. Recent work estimates at least half of observed trends in forest wildfire may be due to climate change (Abatzoglou and Williams, 2016). Many studies predict continued increases in large fire occurrence with climate change in western US forests (Spracklen et al., 2009; Littell et al., 2010; National Research Council, 2011; Westerling et al., 2011a, 2011b; Kitzberger et al., 2017).

Area burned in high severity fire has been correlated to total area burned in some regions, and has seen a concomitant increase with increasing fire size (Cansler and Mckenzie, 2014; Dillon et al., 2011; Miller et al., 2009; Miller and Safford, 2012; Abatzoglou et al., 2017). In the North Cascade Range, Cansler and McKenzie found that both total high severity area and patch size increased with total burned area (2014). Bottom-up controls, such as topography and vegetation, appeared to mediate this fire area-burn severity area relationship in some ecosystems with historical low-moderate severity fire regimes (Cansler and McKenzie, 2014).

In the Sierra Nevada Mountains, California and Nevada, Miller et al., found that fire size (annual mean and maximum) and total area burned increased in the period 1984–2006, and are now above pre-suppression levels prior to 1935 (2009). They also found that the proportion of high severity, stand-replacing fires increased (Miller et al., 2009). The proportional increase in high severity fires was not uniform, but was concentrated in low to mid-elevation forest types where 25–40% of total burned area was classed as high severity. High severity fires are not characteristic of these forest types, indicating that the current fire regime in these ecosystems is outside of historical natural

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conditions (Agee et al., 1978; Agee, 1998; Collins et al., 2009; Moody et al., 2006; Parsons and DeBenedetti, 1979).

Previous work (Keyser and Westerling, 2017) indicates that fire year climate is critical to accurately predicting severe fire occurrence, especially for very large fires. While many studies have now sought to explain what controls the occurrence of high severity fire at the individual fire to regional scales, few have looked at what controls the scale at which high severity fire occurs. Abatzoglou et al., (2017) found weak to moderate correlations between metrics of fuel aridity and regional burn severity. The ability to predict the amount of area that is at risk of burning in high severity fire and whether this is changing would improve the implementation of management decisions to mitigate fires with severity that is uncharacteristic in size or for the ecosystem in which it occurs. In this paper, we seek to answer the following questions:

Given that a large fire (> 400 ha) occurs,

1. What is the probability that > 200 ha will burn in high severity?
2. What are the total hectares burned in high severity?
3. What variables determine area burned in high severity?

2. Methods

2.1. Spatial and temporal domain of analysis

As with the presence/absence modeling in Keyser and Westerling, our modeling domain is a 12 km × 12 km latitude/longitude grid of eleven Western US states (2017). We developed models for the Western US as a whole and three smaller regions to determine if we could improve model performance in years with very large high severity area burned in: the Sierra Nevada Mountains (SN), the Northern Rocky Mountains (NR), and mountains in Arizona and New Mexico (hereafter Southwest, SW) (Fig. 1). The data used vary in spatial resolution from 30 m to 12 km; to maintain information content of the higher resolution data, we aggregated it to the 12 km modeling grid by calculating fractional area of each variable.

The temporal domain of analysis is determined by the availability of burn severity data, which is produced with Landsat imagery. Our models are built on data from 1984 to 2006, the latest year of completed burn severity mapping when we started our project. We have since obtained data from 2007 to 2014; trends in fire severity metrics are calculated for 1984–2014. Both our hydroclimate predictor variables and dates within the burn severity database are monthly. We modeled the monthly probability of high severity fire area over 200 ha and total high severity burned area in the Western US and summed to annual values from 1984 to 2006. The ignition date of the fire is provided with the burn severity data, but there is no data on length of fire activity; we used the ignition month to link our hydroclimate predictor variables. Our predictors represent the month that the fire started, but may not represent the exact conditions when high severity fire occurred as many large fires burn for more than one month. Any climatic variability that might drive fire behavior, and thus severity, in a fire burning outside the month of discovery will not be captured in our data.

2.2. Burn severity data

We downloaded fire severity data from the Monitoring Trends in Burn Severity (MTBS) project website and used the classified fire severity images to build our models (Eidenshink et al., 2007, http://www.mtbs.gov). The classified images threshold the continuous differenced normalized burn ratio into five severity classes: unburned to low severity, low severity, moderate severity, high severity, increased greenness. For this analysis we selected only forest fires, defined as a fire in which at least 10% of the total burned area was in forest vegetation, following USFS classification standards (Brohman and Bryant, 2005). We used data included with the MTBS data that intersects fire severity pixels with Ecological Systems classifications, based on the National Landcover Data Classification (http://www.mtbs.gov/ProjectDocsAndPowerpoints/projectplan.html; 29 January 2016, Homer et al., 2007). We calculated the fractional fire area, for all classes, in the following broad classifications: barren, developed, forest, herbaceous natural, herbaceous planted, shrubland, water, wetlands. We dropped 41 fires from our classified burn severity data that did not have a matching record in the ancillary vegetation/severity database. Of a total 4591 fire records in the MTBS burn severity and vegetation database files (1984–2006), we retained 1871 fires that were a minimum of 400 ha, had forest cover ≥10% and had matching records in the classified severity and severity by vegetation database files. We intersected the burn severity images with the 12 km grid; if a fire intersected more than one modeling pixel, we assigned it to the pixel containing the majority of the fire area.

We set the presence of high severity fire hectares > 200 as the threshold for this analysis. Of the 1871 forest fires, 815 exceeded the 200 ha high severity threshold. The 200 ha threshold was selected for the generalized Pareto distribution models for area exceeding that threshold using graphical analysis to fall within the range where the sample mean excess function is a linear function of the threshold value (see Coles, 2001; Holmes et al., 2008).

2.3. Landscape data

Topographic variables derived from the GTOPO30 global 30 Arc Second (1 km) Elevation Data Set data were aggregated to our 12 km modeling resolution. These were accessed online from the North American Land Data Assimilation System (LDAS) (http://ldas.gsfc.nasa.gov, Mitchell et al., 2004). The variables include minimum, maximum, mean and standard deviation of elevation within each modeling pixel. Mean slope and aspect are also included. The standard deviation of elevation reflects the topographic complexity within each modeling pixel. We also created a two dimensional surface spline of latitude and longitude to use as a smoothed spatial dummy variable for site-specific characteristics (*as in* Preisler and Westerling, 2007).

We aggregated fire regime condition class (FRCC) data from the LANDFIRE project (accessed online at http://www.landfire.gov) as the fractional coverage of each class within the 12 km modeling pixels; we then normalized the FRCC fractions using the log function. Fire regime condition class is a widely used metric to identify the impact of land management decisions on ecosystems. It quantifies differences in current vegetation composition from the range of variability under historical natural fire regimes; the departure value is a continuous value 0–100 (Hann, 2004; Laverty and Williams, 2000). The historical range of variability is determined using the LANDSUM disturbance and succession model run with historic fire regimes (Keane et al., 2006; Pratt et al., 2006). The LANDFIRE departure metric refers only to vegetation composition and does not incorporate changes in fire regime. The departure values are categorized into three FRCC classes: FRCC1 is within historical range of variability (departure < 33%); FRCC2 is moderately departed (33% ≥ departure < 66%); FRCC3 is highly departed, or outside the historical range of variability (departure ≥ 67%) (Holsinger et al., 2006; Keane et al., 2007). We are using the FRCC as a proxy variable to reflect the effects of fire suppression, recognizing that other factors can alter vegetation condition.

2.4. Climate and hydrologic data

We obtained a suite of hydroclimate predictor variables output from the Variable Infiltration Capacity model (VIC) and the gridded climate data used to force it. The VIC model calculates surface and energy water balances and is designed for large-scale applications; it has a simplified soil-vegetationatmosphere-transfer scheme with a two-layer soil module (Liang et al., 1994). A unique feature of VIC is its ability to account for sub-grid scale variability in vegetation characteristics; it