

A Synthesis and Meta-Analysis of Ponderosa Pine Fire Regimes From Five U.S. Regions

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BACKGROUND

A fire regime describes the role fire plays in an ecosystem for a given location and over a specific time period (Agee 1993). The concept is multivariate in nature (Krebs et al. 2010) and therefore is best described by a combination of parameters including fire frequency, severity, extent, seasonality, and relationship with climate. How these parameters vary across space and time and with environmental factors (e.g., elevation and latitude) reveals the underlying dynamics that constitute the fire regime for a given ecosystem. Fire regimes of forest communities are commonly described as high frequency-low severity, low frequency-high severity, or variable frequency-mixed severity; emphasizing the central role of fire frequency and severity in fire regime characterization and suggesting an inverse relationship between these two key parameters.

Fire history studies quantify the values of fire regime parameters, most often fire frequency, but despite an appreciable amount of fire history research within dominant forest types, individual studies are constrained in their scope of inference and restricted in their ability to identify fundamental patterns and relationships across broad scales. Moreover, studies conducted in the same ecosystem may arrive at different conclusions regarding characteristics of a fire regime, yet it is difficult to determine whether differences are driven by underlying natural processes, or by variability in researcher approach

(e.g., methods, sampling design, terminology, etc.). For example, fire history studies in ponderosa pine (*Pinus ponderosa*) ecosystems of the Colorado Front Range provide estimates of historical fire frequency (mean fire-return interval, MFI) that range from 3 years (Gartner et al. 2012) to 66 years (Laven et al. 1980), and fire-severity estimates (i.e., the proportion of events that are classified as low, mixed, and high severity) that range from 0 percent (Schoennagel et al. 2011) to 90 percent for low-severity class fires (Ehle and Baker 2003), and 0 percent (Sherriff et al. 2014) to 64 percent for high-severity class fires (Williams and Baker 2012). Understanding the role of natural variability in determining fire regime characteristics of a given forest type is even more challenging across broad spatial extents than within a specified region. Literature reviews coupled with a quantitative assessment of the distribution of fire regime parameter values from individual studies can help explain variability among studies, identify areas where disagreement is largely due to researcher approach, and reveal fundamental patterns from natural relationships.

A wealth of research has been conducted on fire history in ponderosa pine ecosystems over the past five decades, leading to multiple interpretations on the characteristics and driving mechanisms of the distribution of key fire regime parameters. We synthesized and quantified this information from five U.S. regions: Northern Rocky Mountains (Fryer 2016),

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

Extended abstracts published in these proceedings were submitted by authors in electronic media. Editing was done for readability and to ensure consistent format and style. Authors are responsible for content and accuracy of their individual papers and the quality of illustrative materials. Opinions expressed may not necessarily reflect the position of the U.S. Department of Agriculture.

Black Hills and surrounding areas (Murphy 2017), Blue Mountains (Juran 2017), Colorado (McKinney, submitted), and East Cascades (Juran and Zouhar, in preparation). Our objective in this current paper is to describe what the collective research indicates about the distribution of fire frequency values within and among the five regions, and to address whether and how fire frequency varies with elevation—a key environmental factor broadly believed to contribute to variability in fire regime parameter values (e.g., Johnson and Larsen 1991 and references therein).

METHODS

We performed a systematic review to address our study objective. We searched several citation databases for relevant literature from each of the five regions using keywords such as fire history, fire regime, ponderosa pine, and geographic location (e.g., Colorado). We also examined the literature cited in relevant studies identified by the initial search to find other relevant publications, including published and unpublished studies that did not turn up in the initial search. Papers were reviewed and included in our analysis if they met the following inclusion criteria: research occurred within one of the five regions in a ponderosa pine-dominated ecosystem, were empirically based, and reported numeric results for fire frequency values. Sixty studies met the inclusion criteria and formed the population of studies for the meta-analysis. When a study included multiple, independent sites, site-level values were extracted and entered in our database.

We extracted mean, minimum, and maximum fire-return interval (years) values, associated time period, elevation (m), and latitude and longitude (decimal degrees) from 60 studies comprising 200 independent sites. Fire-return interval estimates in these studies were based almost exclusively on fire-scars, which provide a record of low- to moderate-severity surface fires. Site elevation, latitude, and longitude were derived using mapping software and were based on site descriptions or maps from the studies when values were not explicitly provided. In cases where there was not enough information to delineate site-specific values, we used study-level values provided in the papers. When only minimum and maximum elevation values were given in papers, we calculated the mid-point value and entered it as the site elevation.

We performed graphical analysis to explore and describe patterns in fire frequency and elevation within and among regions by creating histograms and box plots of all MFI and elevation values. We then plotted MFI value by corresponding site elevation and calculated Pearson's correlation coefficient between MFI and elevation to assess the strength of the linear relationship between the two variables within each region and for the complete data set. Finally, we calculated summary statistics of central tendency and variability to compare MFI and elevation within and among regions.

RESULTS

The mean MFI for all 200 sites was 18.2 years ($\pm$ SE 0.7 years) and ranged from 3 to 66 years. Mean elevation was 1,818 m ($\pm$ SE 43.4 m) and ranged from 550 m to 3,078 m. Despite the broad spread between minimum and maximum values for both variables, the standard errors relative to the means (RSE) were quite low (RSE MFI = 4.1 percent, RSE elevation = 2.4 percent). Site-level MFI increased with elevation across the 200 sites ($r = 0.36$, $P < 0.05$).

The spread of MFI values varied among regions, but median MFI values were similar among regions, except for East Cascade sites, where the 95 percent confidence interval for the median was shorter than all other regions except the Northern Rockies (fig 1a). Variability in the range of elevation values among the five regions was much larger compared to MFI values (fig 1b). Median elevation was significantly greater in Colorado than all other regions; Black Hills and Blue Mountains were not different from each other, but were significantly higher in elevation than East Cascades and Northern Rockies (fig 1b). Likewise, the strength of the relationship between elevation and MFI varied broadly among the regions (fig 2). We found a significant relationship ($P < 0.05$) between elevation and MFI in the Black Hills, Northern Rockies, and Colorado, while elevation at sites in the East Cascades and Blue Mountains had positive, but weak associations with MFI (fig. 2).

Elevation range within regions explained variability in the strength of the relationship between elevation and MFI among regions except for the East Cascades where the correlation was the second lowest ($r = 0.14$)

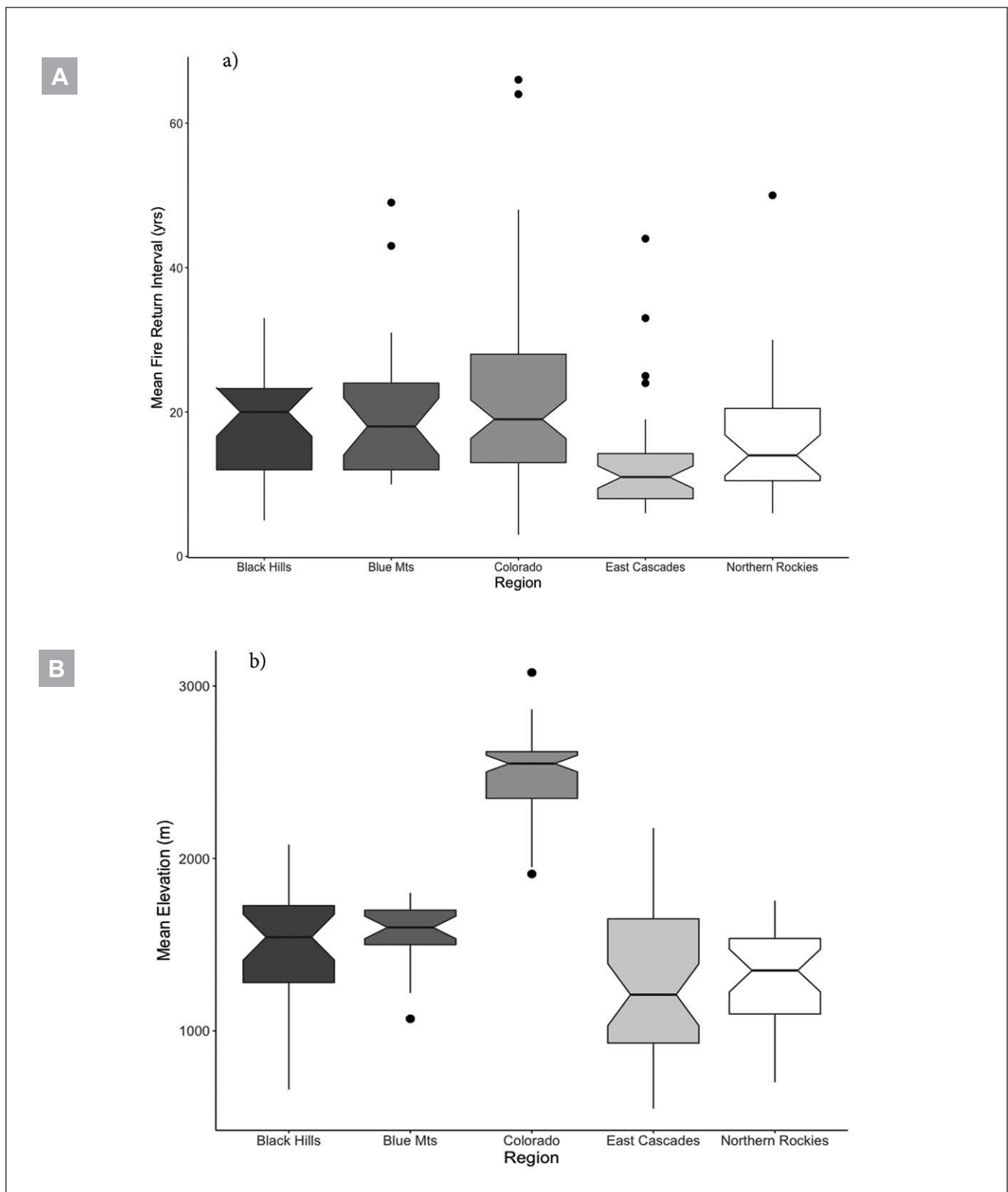


Figure 1—Variability in site-level mean (A) fire-return interval and (B) elevation by five geographic regions from 60 fire history studies on ponderosa pine (*Pinus ponderosa*) dominant communities. The line in the middle of each box represents the median value (50th percentile), the ends of the boxes are the first (Q1) and third (Q3) quartiles, which cover the central 50% of the data, and the difference between Q3 and Q1 is the interquartile range (IQR). Vertical lines extend to the most extreme data points that are no more than $\pm 1.5 \times \text{IQR}$, and outliers beyond the vertical lines are individually displayed as circles. Regions whose notches do not overlap have median values that are not different with 95 percent confidence.

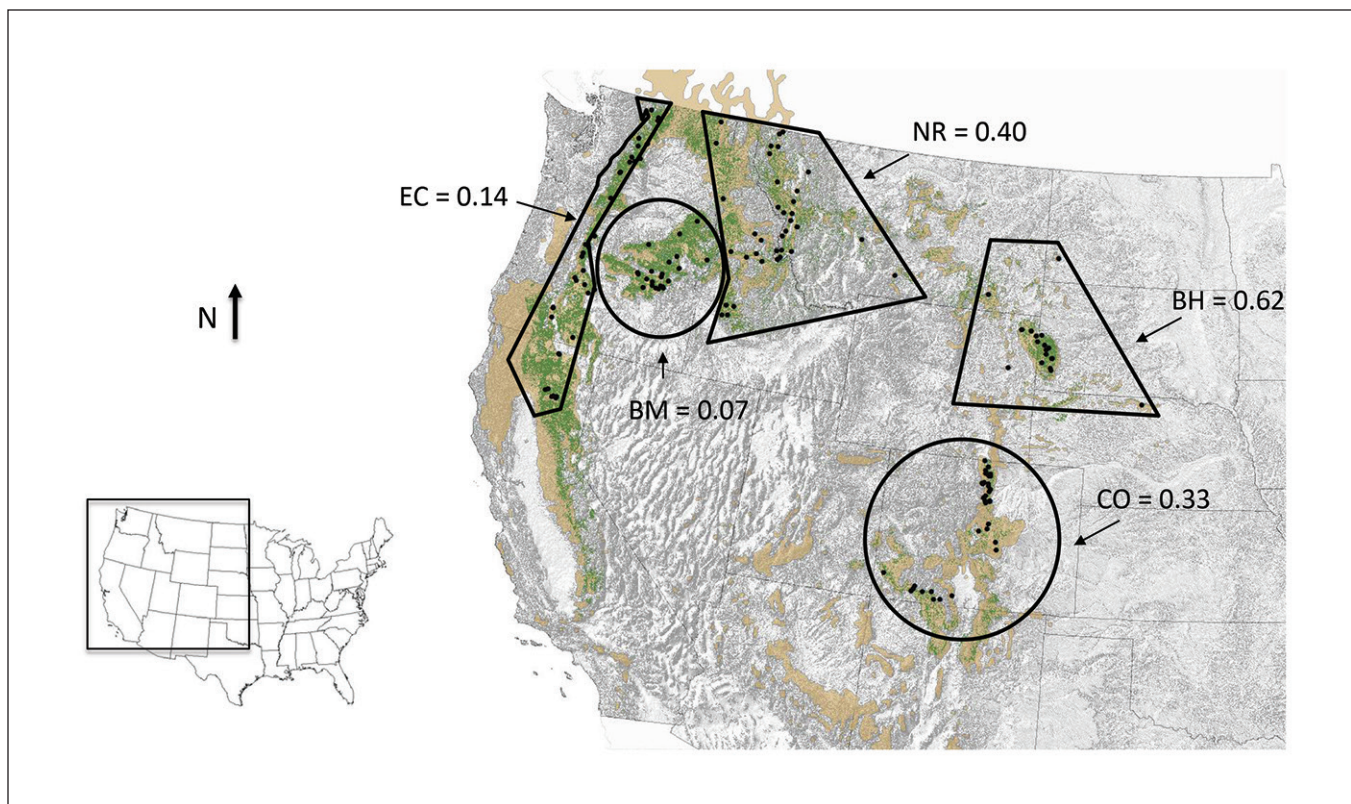


Figure 2—Distribution of ponderosa pine (tan = species (Little 1971), green = Biophysical Settings within study regions (LANDFIRE 2008)). Black dots indicate approximate location of study sites used in this meta-analysis. The five study regions are delineated with black polygons, with study region abbreviation and associated correlation coefficient value between site-level mean fire return interval (years) and elevation (m) given. Abbreviations: EC = East Cascades, BM = Blue Mountains, NR = Northern Rockies, BH = Black Hills and surrounding area, and CO = Colorado.

but elevation range was largest (1,625 m). The value of the correlation coefficient increased steeply with elevation range among the four other regions from a low in the Blue Mountains ($r = 0.07$, elevation range = 730 m) to a high in the Black Hills ($r = 0.62$, elevation range = 1,420 m).

The strongest and most consistent relationship between elevation and MFI was evidenced at the regional level ($r = 0.79$, $n = 5$). The East Cascades had the shortest MFI (12.9 years) and lowest mean elevation (1,287 m), followed by the Northern Rockies (15.7 years, 1,301 m), Black Hills (18.4 years, 1,514 m), Blue Mountains (19.7 years, 1,565 m), and Colorado (21.3 years, 2,479 m).

CONCLUSIONS

Our analysis of data from 200 ponderosa pine community sites in five regions suggests that variability in fire frequency and the strength of its relationship with elevation are dependent on the

spatial scale of analysis. Our understanding of both the variability in fire frequency and its relationship with elevation is limited at the site level, where other factors can strongly affect variability in fire frequency values. Mean fire return interval values will be difficult to predict based only on site elevation, therefore. Indeed, myriad other factors, including history of grazing, logging, mining, and fire suppression activity likely contributed to the wide range of site-level MFI we encountered in the literature.

At broader spatial extents (i.e., among regions), more consistent patterns emerge. Ponderosa pine mean fire frequency is not too variable at the regional level, and the variation present can be largely explained by changes in elevation. The consistent median MFI values among regions contrasted with the broad spatial and elevational distribution of the sites. The data spanned 11.8° latitude and 23.4° longitude, and were distributed along 2,528 m of elevation, yet the range in regional-level MFI was only 8.4 years. This suggests

that at the regional level the conditions that favor ponderosa pine occurrence provide for a reasonably consistent environment for high frequency-low severity fire.

Elevation can reflect a change in environmental conditions, where, in general, precipitation increases and temperature decreases with increasing elevation. These changes can manifest into variability in fire frequency through complex relationships with fuel dynamics. For example, in Colorado, lower elevation sites can be fuel limited and require moist conditions to generate fine fuels to carry fires, while higher elevation sites can have sufficient fuel to carry fires but the likelihood of fire is affected by the dryness, and not the lack of abundance, of those fuels (Gartner et al. 2012; Sherriff and Veblen 2008). Elevation provided one explanation for variability in fire frequency at coarse scales across the broad study area, demonstrating that this key variable can be a useful indicator of fire frequency within the species' environmental space.

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