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A 1,500-year synthesis of wildfire activity stratified by elevation from the U.S. Rocky Mountains

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ABSTRACT

A key task in fire-climate research in the western United States is to characterize potential future fire-climate linkages across different elevational gradients. Using thirty-seven sedimentary charcoal records, here we present a 1500-year synthesis of wildfire activity across different elevational gradients to characterize fire-climate linkages. From our results, we have identified three periods of elevated fire occurrence centered on the 20th century, 900 cal yr BP, and 1350 cal yr BP. During the 20th century, fire activity has occurred primarily in the northern Rocky Mountains, with mid-elevations experiencing the greatest increase in wildfire activity. While wildfires occurred primarily in the SRM region ~900 cal yr BP, the greatest increase in high-elevations occurred in the NRM at this time. Finally, synchronous wildfires occurred in both northern and southern Rocky Mountain mid-elevations ~1350 cal yr BP, suggesting a potential analog for future wildfire conditions in response to warmer temperatures and more protracted droughts. We conclude that wildfire activity increased in most elevations during periods of protracted summer drought, warmer-than-average temperatures, and based on modern climate analogs, reduced atmospheric humidity.

1. Introduction

Fire is considered to be an important natural disturbance because of its ecological role in releasing nutrients, influencing stand composition, reducing biomass, and increasing biodiversity in many forested ecosystems across the western United States (U.S.) (Agee, 1993; Cruzten and Goldammer, 1993; Mutch, 1994; Keane et al., 2002; Dunnette et al., 2014). Over the past 30 years, there has been an increase in the number of large wildfires, as well as an increase in the area burned across many ecoregions of the western U.S. (Dennison et al., 2014). The recent increase in wildfire activity has been linked to both longer and warmer summers, as well as increased drought severity over the past two decades (Westerling et al., 2006; Clark et al., 2016). Climate model projections suggest a minimum increase of ~2 °C in average global temperatures by the end of the 21st century, which will likely lead to more intense droughts, increased precipitation variability (Romero-Lankao et al., 2014), and increased fire frequency and fire severity (Flannigan et al., 2009; Liu et al., 2016). As forested ecosystems are expected to shift towards novel-disturbance regimes in the western U.S. (e.g. Allen et al., 2011; Westerling et al., 2011), it is important to understand which ecosystems are the most susceptible to shifts towards novel-disturbance regimes.

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A key task in fire-climate research in the western U.S. is to characterize potential future fire-climate linkages across different elevational gradients. During the past several decades, mid-elevation montane forests have been the most susceptible to temperature-driven increases in wildfire activity, particularly in the northern Rocky Mountain region (Westerling et al., 2006). Using knowledge of past fire-climate linkages during previous warm periods, such as during the Medieval Climate Anomaly (MCA; 1000–700 cal yr BP) (Mann et al., 2009), reveals greater incidence of wildfires (i.e., biomass burning) under warmer temperatures and drought conditions across much of the western U.S. (Marlon et al., 2012). However, because temperature variability appears to be a significant control on wildfire activity at both mid- and high-elevations (Schoennagel et al., 2004), projected future warming in mid-elevation montane forests may represent one of the most vulnerable ecosystems to novel-disturbance regimes.

Reconstructed fire-climate indices using primarily fire-scars and tree rings have shown that large wildfires in the northern Rocky Mountains have occurred during years of warmer-than-average spring temperatures, and warm and dry summers (Kitzberger et al., 2007; Heyerdahl et al., 2008). However, these fire histories are typically limited to low elevations where moderate-to-high severity fire regimes generally do not occur. Lake sediment records provide the only reliable method to obtain quantitative information about long-term ecological processes (Willis et al., 2010). Of these data, sedimentary charcoal are the most widespread proxy for reconstructing fire occurrence and regional trends in wildfire activity on varying time and spatial scales, and provide information regarding the potential impacts of climate variability on fire activity (Power et al., 2008; Marlon et al., 2012). However, regional paleofire reconstructions are limited to geographic regions with higher record densities (Power et al., 2008). For example, merging charcoal records on regional-to-continental scales and across different vegetation types, climate zones, and human population densities could dilute the importance of climate versus vegetation and human controls on wildfire activity through time (Blarquez and Aleman, 2015). However, when compared to the early Holocene, vegetation composition has remained relatively stable in the U.S. Rocky Mountains over the past 1500 years until the modern period (Anderson et al., 2008; Brunelle et al., 2005; Carter et al., 2013; Higuera et al., 2014), and provides an opportunity to explore the importance of fire-climate linkages. Additionally, prior-to Euro-American settlement (~1850 CE), indigenous human populations likely had minimal impact on mid-to-high elevation fire regimes in the U.S. Rocky Mountains (Schoennagel et al., 2004), thus making this region an ideal study region to understand fire-climate relationships.

Here, we present a regional-scale reconstruction of paleofire history from different elevational gradients from the northern Rocky Mountains (NRM) and southern Rocky Mountains (SRM) over the past 1500 years inferred from a new compilation of sedimentary charcoal records. Specifically, we explore sedimentary charcoal records across elevational gradients to determine whether the recent increase in wildfire activity at mid-elevation forests is unprecedented in both time and space. We hypothesize that over the past 1500 years, periods with significant changes in fire activity occurred in response to warmer-than-average temperatures and lower-than-average seasonal moisture in mid-to-high elevation Rocky Mountain montane forests. We focus on three periods of extreme fire activity; the mid-20th century, ~900 cal yr BP, and ~1350 cal yr BP.

2. Regional setting

2.1. NRM and SRM climate

The U.S. Rocky Mountains are typically partitioned into the NRM and SRM units based on the major winter climate boundaries identified by Mitchell (1976). Here, we used the original boundaries identified by Mitchell (1976), as well as used 42°N latitude as a geographic transition point between the two climate regions that generally correspond with the El Niño Southern Oscillation (ENSO) transition zone (Dettinger et al., 1998; Wise, 2010) (Fig. 1).

Due to the complex topography of the U.S. Rocky Mountains, climate and vegetation communities are influenced by local orographic effects, which promote steep precipitation gradients, rain shadows, and differences in insolation receipt (i.e., aspect). Broadly, winter storms originating from the Pacific Ocean are moisture laden, which result in a winter snow-dominant precipitation regime in the NRM region, with 50–80% of the annual precipitation falling during the winter months of December, January, and February (DJF) (Fig. 1). In the SRM region, winter storms generally lose much of their moisture crossing the Sierra Nevada range and Intermountain West (Kittel et al., 2002). However, while the SRM region does receive winter moisture in mountainous areas due to orographic effect, the SRM are generally more influenced by summer precipitation than the NRM region (Fig. 1). In the NRM, the timing of peak precipitation generally varies between February and May (Shinker, 2010), while the timing of peak precipitation in the SRM varies between May and August, depending on the geographical position and influence of the North American Monsoon (Shinker, 2010).

2.2. Modern fire-vegetation-climate linkages in the NRM and SRM regions

Throughout the NRM and SRM, low-to-mid-elevation conifer forests are generally dominated by Ponderosa pine (*Pinus ponderosa*), quaking aspen (*Populus tremuloides*) and Douglas-fir (*Psuedotsuga menziesii*). Ponderosa pine forests typically experience frequent, low-to-moderate severity wildfires, while Douglas-fir forests typically experience infrequent, yet variable severity wildfires (Baker, 2009). Fire-climate linkages in low-to-mid-elevation conifer forests of the SRM can be attributed to oscillating teleconnection patterns associated with ENSO (Swetnam and Betancourt, 1998). Generally, La Niña years are associated with lower-than-average winter precipitation and increased fire activity during the summer in the SRM (Schoennagel et al., 2005), while in the NRM, La Niña years are associated with high snowpack and reduced wildfire activity (Heyerdahl et al., 2008). However, the opposite pattern occurs during El Niño years, which delivers high snowfall to the SRM, and lower-than-average snowfall in the NRM. In general, wet antecedent conditions promote the buildup of fuels in low-elevation grasslands, woodlands, and forests, which facilitate the spread of wildfires in both the NRM (Morgan et al., 2008) and SRM. Therefore, low-to-mid-elevation conifer forests can be characterized as being ‘fuel-limited’ systems (Schoennagel et al., 2004).

High-elevation conifer forests that generally include lodgepole pine (*Pinus contorta*), subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engelmannii*) across both regions typically experience a fire regime characterized by infrequent, stand-replacing burns. These forests are abundant in fine fuels, particularly among the duff layer. As a result of a limited snow-free

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