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Climatic influences on fire regimes in ponderosa pine forests of the Zuni Mountains, NM, USA

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ABSTRACT

We characterized fire history and examined climate–fire relationships in dry ponderosa pine (*Pinus ponderosa*) forests in the Zuni Mountains of northwestern New Mexico. Our findings indicate that the historical wildfire regime for the study area was typified by high-frequency, low-severity surface fires. Climate–wildfire relationships were assessed using both Superposed Epoch Analysis (SEA) and Bivariate Event Analysis (BEA). SEA revealed that interannual variability of the El Niño–Southern Oscillation (ENSO) and the Palmer Drought Severity Index (PDSI) was a strong driver of widespread wildfires; wetter conditions often occurred one to two years prior to fire and were followed by drought during the fire year. BEA revealed statistically significant relationships only in the case of extreme PDSI events and widespread wildfire in the year of fire ($t = 0$). No relationship was found between either the Pacific Decadal Oscillation (PDO) or the Atlantic Multidecadal Oscillation (AMO) and widespread fire occurrence, signifying that shorter-term (i.e. interannual) oscillations between wet and dry conditions, rather than longer-term climatic variability, were historically most conducive to fire. Contextualizing these findings under ongoing climate and land-use change is challenging. Full restoration to historical conditions may be neither possible nor desired, but targeted efforts to promote a frequent, low-severity wildfire regime are generally consistent with our understanding of historical fire activity in this forest type and may foster ecological, economic, and/or societal goals.

1. Introduction

Wildfire is a prominent disturbance in forested ecosystems and is driven in part by interannual to multidecadal climate variability (Bowman et al., 2009; Flannigan et al., 2009; Kitzberger et al., 2007; Westerling et al., 2003). Further understanding of how climate variability affects wildfire activity is needed to guide managers and policy makers as they face difficult decisions regarding issues such as fuels management, firefighting, and post-fire rehabilitation practices under varying scenarios of climate and land-use change. The relationships between climate variability and current and future fire activity are complex but can be greatly informed by knowledge of past climate–wildfire interactions (Landres et al., 1999; Wiens et al., 2012). In dry ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson) forests of the southwestern USA, human-caused alterations (e.g., grazing, logging, and fire suppression) have led to current forest stand conditions that differ significantly from those of the past (Allen et al., 2002; Covington and Moore, 1994; Covington et al., 1997). However, climate remains an important driver of wildfire activity even in areas where anthropogenic change has been significant (Littell et al., 2009; Westerling and Swetnam, 2003; Westerling et al., 2006). Given the societal, economic, and ecological consequences that can result from fire activity that is outside of the historical range of variability, additional research regarding historical wildfire regimes and climate–wildfire relationships is needed. In this study, we assess historical wildfire regimes in ponderosa pine forests of the Zuni Mountains of northwestern New Mexico and examine how interannual to multidecadal climate variability influenced the occurrence of widespread wildfire.

Typical climate conditions associated with wildfire activity differ markedly from one forest type to another. The spatial heterogeneity in patterns of climate–wildfire interactions at broad scales is related to differences in biomass availability (Krawchuk and Moritz, 2011; Moritz et al., 2012; Pausas and Ribeiro, 2013; Whitlock et al., 2010). In wetter areas characterized by high biomass availability, increased wildfire activity often occurs

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following prolonged periods of drought. In contrast, in drier areas where biomass is relatively limited, increased fire activity is often associated with above-average moisture conditions one or more years prior to fire, followed by drought in the fire year. In the latter case, low fuel availability constrains the occurrence of wildfire and antecedent moisture conditions are thus first needed to promote fuel accumulation. In dry ponderosa pine forests of the southwestern USA, relatively biomass-limited, grassy fuels were historically dominant and antecedent moisture conditions were typical before fires (Grissino-Mayer and Swetnam, 2000; Swetnam and Betancourt, 1990, 1998). Wetter conditions likely promoted higher grass fuel amount and continuity, thereby increasing the potential for fire spread.

Research focused on fire–climate interactions in western North America has increasingly included assessment of longer-term, broadscale climate drivers of fire (e.g., Kitzberger et al., 2007; Schoennagel et al., 2007; Trouet et al., 2010; Westerling and Swetnam, 2003). The El Nino–Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO) have been of particular interest. Both ENSO and PDO involve oscillations of Pacific Ocean sea–surface temperatures between warm (positive) and cool (negative) phases. ENSO shifts on a cycle of approximately 2–7 years and is associated with sea–surface temperature anomalies in the equatorial Pacific (Diaz and Markgraf, 2000), while PDO oscillates at periodicities of 20–30 years and is associated with sea–surface temperature anomalies in the northern Pacific (Mantua et al., 1997). The AMO is measured by annual sea–surface temperature anomalies in the North Atlantic Ocean and oscillates between phases approximately every 50–70 years (Kerr, 2000). Because instrumental climate records are relatively short, studies of historical fire–climate relationships frequently rely on climate reconstructions based on proxies such as tree rings. In many cases, multiple reconstructions are available for the same climate pattern (see National Climatic Data Center, 2013). In the case of PDO, the variability between different reconstructions is significant and results of analyses of PDO and wildfire may differ markedly depending on the particular reconstruction used (Kipfmueller et al., 2012).

Climate–wildfire studies commonly employ Superposed Epoch Analysis (SEA) to examine interannual relationships between fire occurrence and a particular climate pattern for relatively short windows of analysis (e.g., Grissino-Mayer and Swetnam, 2000; Swetnam, 1993; Trouet et al., 2010). As interest in longer-term climate oscillations such as PDO and AMO has increased, so has the need for methods suitable for testing relationships spanning longer timescales (Schoennagel et al., 2007). Recent studies have employed Bivariate Event Analysis (BEA) via the K1D software (Gavin, 2010) to examine longer-term interactions between climate variability and wildfire (Gartner et al., 2012; Schoennagel et al., 2007). In the current study, we assessed wildfire–climate relationships in ponderosa pine forests of the Zuni Mountains in northwestern New Mexico at interannual to multidecadal timescales using both SEA and BEA, an approach not previously employed in this forest type (i.e. southwestern ponderosa pine). We also examined the effect of combined phases of ENSO, PDO, and AMO on widespread fire activity. Our research objectives were to: (1) characterize historical wildfire activity in terms of fire frequency and synchrony, and (2) assess the relationship between widespread fire occurrence and interannual to multidecadal climate variability. Based on previous findings in southwestern ponderosa pine systems (e.g., Grissino-Mayer and Swetnam, 2000; Swetnam and Betancourt, 1990, 1998) and our conceptual understanding of typical climate–wildfire relationships in relatively biomass-limited systems with grassy fuels, we hypothesized that fires occurred relatively frequently in our study area and that short-term fluctuations of PDSI and ENSO were important drivers of fire occurrence.

2. Methods

2.1. Study area

The study area is located in the Zuni Mountains of northwestern New Mexico, on the southeastern edge of the Colorado Plateau. The mountain range is situated almost entirely within the Mount Taylor Ranger District of Cibola National Forest. Data from the nearest weather station (El Morro National Monument, 1938–2013) show that the mean maximum January temperature is approximately 6.2 °C, the mean maximum July temperature is approximately 29.4 °C, and total annual precipitation is approximately 351 mm (Western Regional Climate Center, 2013). Precipitation patterns vary over the course of the year, with the largest peak in precipitation typically occurring in the summer along with the North American Monsoon. The study area is also characterized by a high degree of interannual variability of precipitation; a number of annual to multiyear droughts and wet periods are documented in the climate record (Sheppard et al., 2002). Across the study area, ponderosa pine is the dominant tree species, although Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Gambel oak (*Quercus gambelii* Nutt.), piñon (*Pinus edulis* Engelm.) and alligator juniper (*Juniperus deppeana* Steud.) are also common. Grasses such as *Muhlenbergia* spp. and Arizona fescue (*Festuca arizonica* Vasey) generally dominate the understory. In dry ponderosa pine forests of the western USA, the legacy of modern human disturbances has often resulted in present wildfire hazard that many consider to be outside the historical range of variability (Grissino-Mayer, 1999; Moore et al., 1999). However, it remains uncertain if and how different aspects of the fire regime (i.e. frequency, severity, size, etc.) may be changing and whether these changes are a consequence of prior human disturbances. In our study area, fire frequency decreased ca. AD 1880 with the advent of livestock grazing, particularly by sheep (Magnum, 1997). Livestock herbivory can reduce fire frequency and extent by removing fine fuels necessary for fire spread (Grissino-Mayer and Swetnam, 1997; Touchan et al., 1995). Shortly after the advent of sheepherding, forests of the Zuni Mountains were further altered by the timber industry beginning ca. AD 1905. Clear-cutting practices were common, and as a result, large portions of the range are now covered in higher-density, second-growth stands with different fuel conditions. Additionally, the forests of the Zuni Mountains were heavily dissected by rail lines and a road network to support the logging industry, resulting in a fragmented landscape that hindered the ability of fire to spread. Lastly, deliberate fire suppression efforts, especially those undertaken following the end of World War II, further reduced fire activity (Cooper, 1960; Covington and Moore, 1994; Grissino-Mayer and Swetnam, 1997).

2.2. Site selection, field sampling, and sample processing

To characterize historical fire activity in our study area, we relied on fire-scar data obtained from four sites in the Zuni Mountains in northwestern New Mexico (Fig. 1). We sampled in areas that were similar in terms of elevation and vegetation type. The sites ranged in size from approximately 30–100 ha, and elevation varied from 2370 to 2610 m (Table 1). Early 20th century logging activity was evident throughout the study area. At each site, we searched for fire-scarred trees following previously established methods (Arno and Sneck, 1977; McBride, 1983). Targeted sampling is standard in fire-history studies and ensures that the fire record is both long and complete (Fulé et al., 2003; Van Horne and Fulé, 2006). A chainsaw was used to collect full cross sections from dead material (i.e. stumps, logs, remnants) as well as non-lethal partial cross sections from living trees. Nearly all samples we