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Annual and decadal climate forcing of historical fire regimes in the interior Pacific Northwest, USA

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Abstract: Anticipating the consequences of climatic change for fire requires understanding of the causes of variation in historical fire regimes. We assessed the influence of annual and decadal variation in climate on fire regimes of ponderosa pine-dominated forests in eastern Oregon and Washington using existing, annually dated tree-ring reconstructions (1687–1994). In four watersheds, we compared the extent of low-severity fires (total area burned each year) to precipitation and the Southern Oscillation Index, a measure of variation in El Niño-Southern Oscillation (ENSO), which affects weather in this region. At the annual scale, large fires burned during dry years and El Niño years (low SOI) in all watersheds while small fires burned regardless of variation in these climate parameters. Large fires also burned during relatively wet years and La Niña years (high SOI) in one watershed, indicating that local factors can override regional climate controls in some locations. Climate from previous years did not influence current year's fire extent. The influence of ENSO on fire regimes in this region has not previously been demonstrated at these multicentury, regional scales. At the decadal scale, fire extent varied with precipitation, perhaps in response to variation in such climate features as the Pacific Decadal Oscillation. Several decades of low fire extent in the watersheds during the early 1800s was synchronous with a lack of fire at other sites in North and South America, probably in response to a change in the global climate that included a lessening in the frequency and/or intensity of ENSO events.

Key words: Fire history, dendrochronology, climate, fire scars, El Niño-Southern Oscillation, Pacific Northwest USA.

Introduction

Understanding past fire-climate relationships allows us to anticipate the future by identifying climate parameters that are likely to affect future fire regimes. Historically, low-severity fires influenced the composition and structure of ponderosa pine-dominated (*Pinus ponderosa*) forests in western North America, including the Pacific Northwest (PNW; Keane *et al.*, 1990; Covington *et al.*, 1994). While estimating the range of historical variation in fire regimes provides a context for current efforts to restore low-severity fires to these forests (Landres *et al.*, 1999; Fulé *et al.*, 1997), it does not allow us to anticipate variation in future fire regimes that may result from changes in climate. Rather, anticipating the consequences of climatic change requires that we understand the *causes* of historical variation in fire regimes (e.g., Swetnam and Betancourt, 1990; Veblen *et al.*, 1999; Grissino-Mayer and Swetnam, 2000).

The influence of past climate variation on fire regimes in the PNW has been explored at short and long timescales, but not at intermediate ones. For example, relative humidity is well documented as a key driver of fire in this and other regions over minutes to days (Schroeder *et al.*, 1966; Deeming *et al.*, 1977) while variation in precipitation is considered to be an important driver of fire frequency over centuries to millennia (Long *et al.*, 1998; Grissino-Mayer and Swetnam, 2000). Despite evidence that climate has varied significantly over years to decades in the PNW (Graumlich and Brubaker, 1986; Graumlich, 1987; Cayan *et al.*, 1998; Dettinger *et al.*, 1998), and was an important driver of historical fire in the southwestern United States (SW; Swetnam and Betancourt, 1990; 1998; Swetnam and Baisan, 1996), the relationship between climate and fire at these timescales is not well understood in the PNW.

Where historical studies have been undertaken, the response of fire to climate is often more complex than fires burning during dry summers (Grissino-Mayer and Swetnam, 2000) and we anticipate the same for the PNW. For example, at annual scales, a significant portion of the variation in winter and spring weather in the PNW is a remote consequence of variation in El Niño/Southern

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Oscillation (ENSO), a coupled air-sea phenomenon near the equator that causes anomalously shallow snow packs during winters following El Niño years (Redmond and Koch, 1991; Cayan *et al.*, 1999). At decadal scales, the Pacific Decadal Oscillation (PDO), an El Niño-like pattern of climate variation focused in the north Pacific basin, affects PNW weather in a manner similar to ENSO but varies on a longer timescale (Mantua *et al.*, 1997; Zhang *et al.*, 1997; Hamlet and Lettenmaier, 1999). We would expect such weather variations to affect fire regimes in the PNW because shallow snow packs melt sooner, resulting in longer fire seasons.

To explore historical fire-climate relationships, we need annual records from periods prior to the twentieth century when timber harvesting, grazing, fire exclusion and other land-use practices nearly eliminated the surface fires that were once common in forests of the interior PNW (Heyerdahl *et al.*, 2001; Wright, 1996; Everett *et al.*, 2000). Archival records are too short for this purpose. Fortunately, multicentury records of both fire and climate are preserved in tree-rings. Within the PNW, the Blue Mountains of northeastern Oregon and southeastern Washington are well suited for examining the influence of climate on historical fire regimes at intermediate timescales because independent records of both climate and fire have been reconstructed for this region from annually dated tree-ring series (Garfin and Hughes, 1996; Stahle *et al.*, 1998; Heyerdahl *et al.*, 2001).

Our objective was to explore the influence of climate on fire regimes in the Blue Mountains at annual to decadal timescales. We compared existing annually dated tree-ring reconstructions of the extent of low-severity fires in four watersheds in the Blue Mountains (Heyerdahl *et al.*, 2001) with precipitation for the southern Blue Mountains (Garfin and Hughes, 1996) and ENSO activity (Stahle *et al.*, 1998). Based on this evaluation, we identified parameters of climate that are likely to affect future fire regimes in this region.

Study area

Vegetation and historical fire regimes

Low-severity fire regimes were reconstructed from tree-rings in four watersheds with similar forest composition in the Blue Mountains (Figure 1; 1687–1994; Heyerdahl *et al.*, 2001). In most of the sampled plots (96%), ponderosa pine dominates or is present in the overstorey. The remaining plots are dominated by Douglas fir (*Pseudotsuga menziesii*) or grand fir (*Abies grandis*). The understorey commonly contains creeping Oregon grape (*Mahonia repens*), common snowberry (*Symphoricarpos albus*), birchleaf spiraea (*Spiraea betulifolia*), serviceberry (*Amelanchier alnifolia*), pinegrass (*Calamagrostis rubescens*), elk sedge (*Carex geyeri*), western yarrow (*Achillea millefolium*), western hawkweed (*Hieracium albertinum*) and heartleaf arnica (*Arnica cordifolia*). Two watersheds were sampled in the northern Blue Mountains and two in the southern portion of this region. In the northern watersheds, Tucannon and Imnaha, the sampled area lies on the north and south slopes of these east–west trending river valleys. In the south, Baker encompasses several perennial streams on the northeastern face of the Elkhorn Mountains at the edge of the broad, flat Baker Valley, and Dugout lies in an area of low relief straddling the north–south trending North Fork of the Malheur River. Elevation in the four watersheds ranges from 976 to 1897 m and slopes are moderate (average at plots: 32%). The sampled watersheds are covered by snow each winter. The modern fire season in these forests typically begins in early to midsummer after the snow has melted and the fuels have dried.

Figure 1 The Blue Mountains of Oregon and Washington, USA, showing the location of the northern (T = Tucannon, I = Imnaha) and southern (B = Baker, D = Dugout) watersheds in which fire extent has been reconstructed (Heyerdahl *et al.*, 2001). Shaded regions indicate land managed by the US Forest Service.

Annual fire extent (total area burned each year) has been reconstructed from annually dated sections of 524 trees (3659 fire scars) sampled in 180 gridded plots covering 2002–8585 ha in the four watersheds (Heyerdahl *et al.*, 2001). Within watersheds, single, contiguous fires were more common than multiple disjunct fires during a given year, with a single fire occurring during 72–93% of the fire years in each watershed. In all watersheds, fire boundaries during most fire years (82%) intersected the edge of the sampled area, suggesting that the actual size of most individual fires was larger than those we reconstructed. Consequently, we believe fire extent to be most accurately reconstructed for Dugout because we sampled a larger area there than in the other watersheds. We analysed fire-climate relationships for the period 1706–1900 because the climate reconstructions begin in 1706 and there was an obvious change in fire extent after 1900 in all watersheds, a period of changing land use in the Blue Mountains (Schwantes, 1989; Irwin *et al.*, 1994; Robbins and Wolf, 1994; Langston, 1995). Before 1900, the time-series of annual fire extent in each watershed varied about a constant mean that was 3–7% of the area sampled (Tucannon = 59 ha, Imnaha = 66 ha, Baker = 253 ha, Dugout = 623 ha; Figure 2).

Modern instrumental climate

The climate of the Blue Mountains is generally continental, with cold winters and warm, dry summers (mean January temperature = −3°C, July = 19°C, 1895–1996; NOAA, 1997). Across this region, annual precipitation is low, falling mainly as snow in winter (mean 446 mm, 1895–1996; EarthInfo Inc., 1990; Mock, 1996). However, climate interacts with landforms, creating a regional-scale gradient in precipitation. Specifically, the Columbia River breaches the Cascade Range west of the northern end of the study area, so moist, westerly Pacific air sometimes brings precipitation to the northern but not the southern portion of the range (Mock, 1996). Climate in the Blue Mountains also varies through time, partly in response to fluctuations in ENSO, a quasi-periodic (2–5 years) coupled air-sea phenomenon that vacillates between two contrasting phases. El Niño (La Niña) is characterized by anomalous warming (cooling) of surface ocean waters in the eastern and central equatorial Pacific Ocean (Enfield, 1992), while the Southern Oscillation is a seesaw in equatorial centres of high and low sea-level pressure (Rasmusson and Wallace, 1983). ENSO events affect weather in the PNW during the following year. Following El Niño (La Niña) events, winters and springs in this region are anomalously dry and warm (cool and wet) resulting in anomalously shallow (deep) snow packs (Redmond and Koch, 1991; Cayan *et al.*, 1999). However, El Niño events have a greater impact on PNW weather than La Niña events (Dracup and Kahya, 1994; Hoerling *et al.*, 1997).

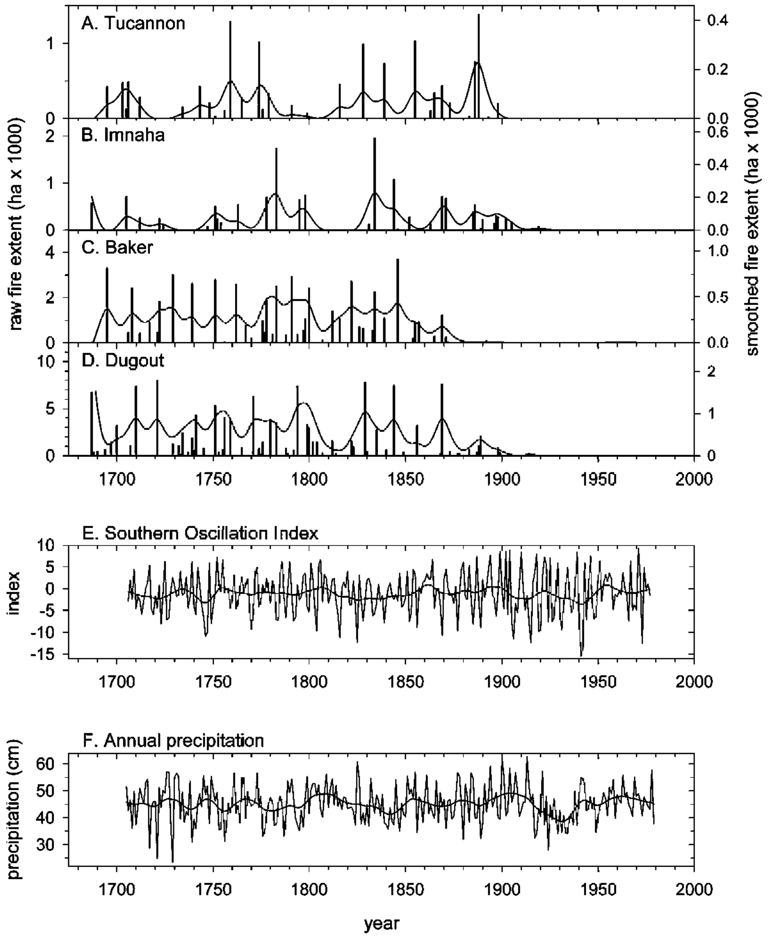

Figure 2 Tree-ring reconstructions of fire extent and climate. Both annual and decadal time-series are shown (cubic spline with 50% frequency cutoff at 20 years). (A–D) Annual fire extent by watershed (from Heyerdahl *et al.*, 2001). (E) Winter Southern Oscillation Index (SOI; December–February; from Stahle *et al.*, 1998). (F) Annual precipitation (previous October–current September) in the southern Blue Mountains of Oregon (from Garfin and Hughes, 1996).

Historical climate from tree-rings

Annual precipitation (sum of previous October to current September) has been reconstructed for the Blue Mountains region from a network of 13 tree-ring chronologies in the Pacific Northwest (1705–1979; Garfin and Hughes, 1996; Figure 2). This reconstruction explains 37% of the variance in instrumental precipitation (1931–79), but captures more of the variation in precipitation for the southern than northern Blue Mountains because most of the trees upon which it was based are in the south and precipitation varies across the region (Heyerdahl, 1997). Consequently, we use this precipitation reconstruction to assess fire-climate relationships only for the southern Blue Mountains. Annual variation in fire regimes in the Blue Mountains is affected by precipitation during two seasons of the year. First, summer precipitation affects fuel moisture directly during the fire season. Second, winter precipitation affects snowcover duration which in turn affects fire regimes indirectly by influencing the length of the fire season. Records of total annual precipitation contain information about both of these seasons.

Variation in the strength and phase of ENSO is captured by an index of the Southern Oscillation, computed as the normalized difference in monthly surface pressure between Tahiti and Darwin, Australia – two measurement stations near the oscillating centres of high and low pressure (Enfield, 1992). Years of low (high) values of the Southern Oscillation Index (SOI) are typically El Niño (La Niña) years (Deser and Wallace, 1987). Winter SOI (December–February) has been reconstructed from 21 tree-ring chronologies from Mexico, the SW and Java, Indonesia (1706–1977; Stahle *et al.*, 1998; Figure 2). This reconstruction explains 53% of the variance in instrumental SOI (1879–1977).

Methods

We examined the annual relationship between fire extent and precipitation in the southern watersheds and with SOI in all four watersheds. We did not assess the relationship of fire extent and

Table 1 Relationship of climate and annual area burned (1706–1900). Values given are significance (p-values) from non-parametric two-sample rank test (Mann-Whitney test; Zar, 1984) used to determine whether significantly more area burned during years of low precipitation (or SOI) than during years of high precipitation (or SOI). Relationships with p-values ≤0.05 were considered significant. The normal approximation to the Mann-Whitney U statistic was computed for all cases except the comparison of fire extent and winter SOI at Imnaha

Climate parameter Watershed	Number of fire years	Mean fire extent (ha × 100) during years when precipitation (SOI) was:		Z	p > Z
		low	high		
Annual precipitation					
Baker	23	11	11	−0.38	0.65
Dugout	20	27	13	1.67	0.05
SOI					
Tucannon	11	5	3	1.49	0.07
Imnaha	11	5	4	270	0.43
Baker	23	14	9	1.50	0.07
Dugout	20	26	11	2.09	0.02

precipitation in the north because the available reconstruction does not adequately capture precipitation variation in the northern Blue Mountains. Within each watershed, we determined whether significantly more area burned (i.e., mean fire extent was greater) during years of low precipitation (or SOI) than during years of high precipitation (or SOI) using the non-parametric two-sample rank test (Mann-Whitney test; Zar, 1984). To investigate lagged relationships, we used superposed epoch analysis (SEA; Haurwitz and Brier, 1981; Prager and Hoenig, 1989; Baisan and Swetnam, 1990; Grissino-Mayer, 1995; Grissino-Mayer and Swetnam, 2000). With SEA, we determined whether average climate (precipitation or SOI) during large fire years (or lagged years) was significantly different from average climate during the years immediately before and after these years (±5 years). We defined large fire years as those during which relatively extensive areas burned, i.e., at least 20% of the sampled area in a watershed. We determined the significance of SEA by bootstrapping (1000 trials; Prager and Hoenig, 1989; Mooney and Duvall, 1993; Grissino-Mayer, 1995).

We examined the decadal relationship between fire extent and precipitation by comparing smoothed annual time-series in each watershed (cubic splines retaining 50% of the variance present in the original series at periods of 20 years; Diggle, 1990).

Results

Current year's climate affected fire extent such that large fires tended to burn during dry years and during El Niño years. In every watershed, large areas (>20% of the sampled area) burned during years of low precipitation or SOI while small fires burned regardless of variations in these climate parameters (Figure 3). Except at Baker, the median area burned was higher during years of low precipitation or SOI than that during years of high precipitation or SOI (Table 1). However, these differences were statistically significant only at Dugout ($p < 0.05$; Table 1) and large fires also burned during relatively wet years and during La Niña years (high SOI) at Baker.

Lagged relationships between climate and fire extent were not significant in any watershed. In the southern watersheds (Baker and Dugout), annual precipitation was significantly low ($p < 0.05$) during fire years as compared with years immediately before and after these years but not during lagged years (±5 years; Figure 4, A and B). Furthermore, SOI was significantly lower during fire years at Tucannon and Dugout but not at Imnaha and Baker, nor for lagged years in any watershed (Figure 4, C–F).

Fire extent was greater during dry than wet decades. Decadal variations in the smoothed series of precipitation and fire extent are strikingly consistent and opposite in sign from the mid-1700s to the mid-1800s at Baker (Figure 5A) and from the beginning of the record until the late 1800s at Dugout (Figure 5B). After ≈1900, fires abruptly ceased burning, although precipitation continued to vary.

Discussion

Climate was a strong driver of historical fire regimes

Annual variation in fire extent in the Blue Mountains was influenced by climate during current, but not preceding, years (Figure 4), probably because the watersheds are covered by snow each winter and the fine fuels that carry surface fires were abundant in these forests. Snow, melting in the spring, increases soil and fuel

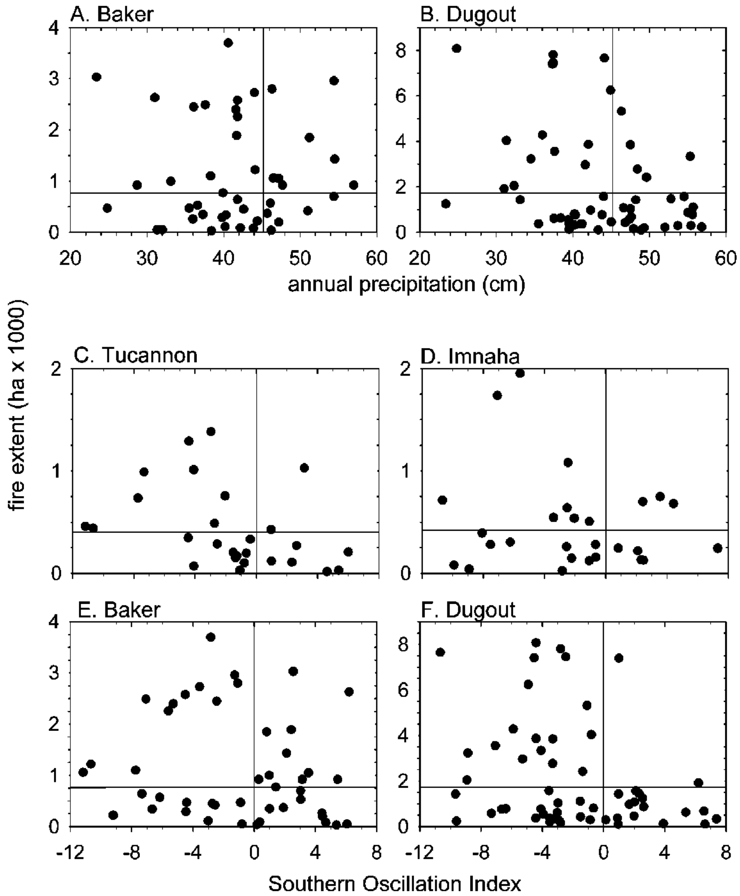

Figure 3 Annual relationship of fire extent and climate (1706–1900). Extent compared to (A–B) reconstructed annual precipitation for the southern Blue Mountains and (C–F) reconstructed winter Southern Oscillation Index (SOI). Horizontal lines indicate 20% of sampled area for each watershed. The vertical line in (A) and (B) is mean annual precipitation (1706–1977).

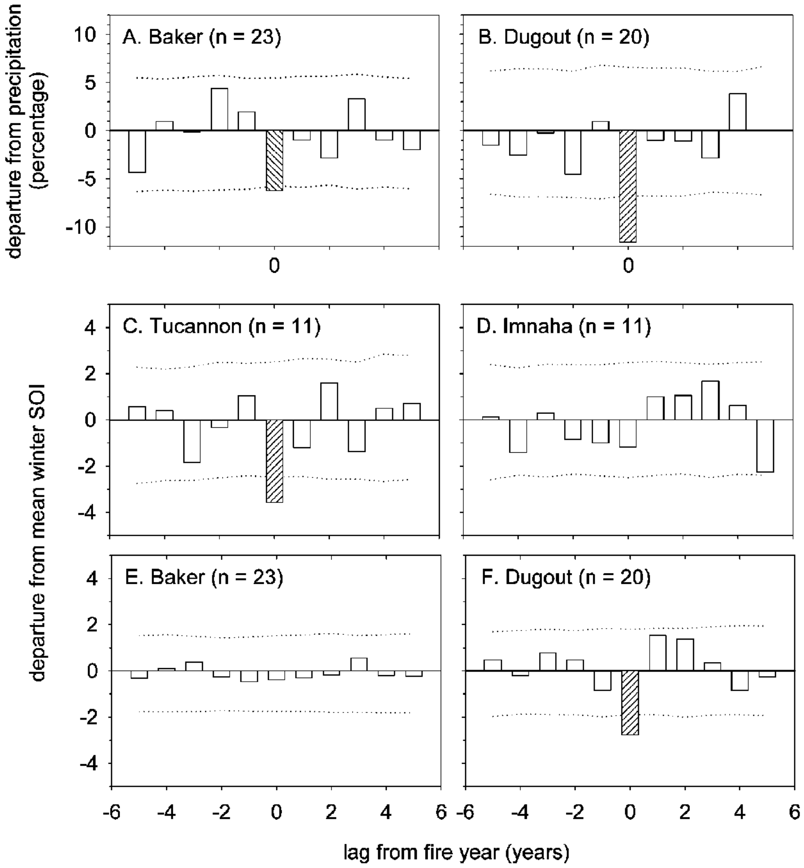

Figure 4 Lagged annual relationship of fire extent and climate (precipitation or winter Southern Oscillation Index (SOI). Average departure from reconstructed climate during relatively large fire years (bars; 1706–1900; extent <20% of area sampled; number of large fire years in parentheses) and for years immediately before and after these years. Departures that fall outside the 95% confidence interval (dotted line) are hatched.

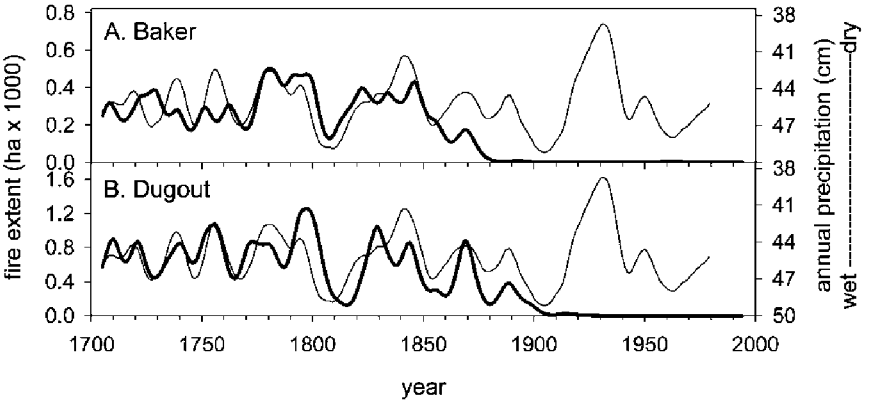

Figure 5 Decadal fluctuations in fire extent and precipitation. Fire extent (thick line) and annual precipitation (thin line), smoothed with cubic splines (50% frequency cut-off at 20 years). The precipitation axis is inverted.

moistures at the beginning of each fire season, so that low fuel moisture during one year does not persist until the next year. Unlike dry ponderosa-pine forests in the SW and Colorado Front Range (Swetnam and Betancourt, 1998; Veblen *et al.*, 2000; Grissino-Mayer and Swetnam, 2000), annual variation in precipitation probably did not cause significant variation in herbaceous and other fine fuels from year to year in the Blue Mountains. Consequently, the potential for fire ignition and spread in the Blue Mountains in a given year is generally unaffected by precipitation or ENSO activity during immediately preceding years.

Historically, annual variation in climate appears to have been a more important driver of fire spread than fire ignition in the Blue Mountains. Large fires burned during relatively dry years in the southern watersheds (Figures 3 and 4), and probably in the northern ones as well, although we were unable to test this inference because we lacked a reconstruction of precipitation for the northern region. Large fires occurred during years of low annual precipitation probably because these years are characterized by low fire-season precipitation and/or shallow snow packs, both of which are conducive to the spread of fires. In contrast, small fires occurred regardless of precipitation, suggesting that fires ignited during any year but only spread during dry years. In contrast to the other watersheds, Baker also experienced large fires during years of high annual precipitation, suggesting that local factors can override the influence of regional-scale climate in some areas (Swetnam and Baisan, 1996). For example, wind influences fire spread but is not captured in reconstructions of either annual precipitation or SOI. Baker's location at the edge of a broad, flat valley may make it prone to more intense or sustained winds than the other three watersheds, which are embedded in more complex terrain.

Annual fire extent also varied with ENSO, a significant source of annual climate variation in the Blue Mountains (Figures 3 and 4). Although there is no evidence that ENSO affects PNW weather during the fire season, it probably influences fire extent by affecting the length of the fire season. Namely, spring snow pack tends to be shallow during El Niño years (low SOI) due to low winter/spring precipitation and warm spring temperatures (Cayan *et al.*, 1999). Shallow snow packs are likely to melt earlier, resulting in longer periods when fires could ignite and/or spread compared to years with deeper snow packs.

Previous studies have shown that ENSO was also a significant driver of annual variation in historical fire regimes in the American SW (Swetnam and Betancourt, 1990; Grissino-Mayer and Swetnam, 2000). However, fluctuations in ENSO have a nearly opposite effect on fire occurrence in the PNW versus SW because the climate response to a given ENSO event differs in the two regions. In the PNW, shorter snowcover duration during El Niño (low SOI) years leads to increased fire spread. In contrast, in the SW, heavy rainfall during El Niño years suppresses fires but increases fine, herbaceous fuel loads in open ponderosa-pine forests, leading to widespread fires in these forests for several years following an El Niño event (Swetnam and Betancourt, 1990; Redmond and Koch, 1991; Cayan *et al.*, 1999). Furthermore, during La Niña years (high SOI) in the PNW, snow pack is deeper than during other years and fire spread is suppressed, whereas in the SW fire-season precipitation is low, facilitating the ignition and spread of fires.

The strikingly consistent decadal variation in climate and fire in the southern watersheds (Figure 5) does not reflect the cumulative effect of multiple years of low or high precipitation, given the lack of lagged annual relationships between climate and fire in the Blue Mountains (Figure 4). More likely, it reflects the fact that low precipitation, leading to low fuel moisture and relative humidity, or to longer fire seasons, is a necessary but not sufficient condition for fire spread. An ignition source and adequate fuel are also necessary (Rothermel, 1983). In the Blue Mountains, when multiyear periods of low precipitation are considered, the probability of satisfying the necessary conditions during one of those years increases. Specifically, fire-season precipitation and lightning strikes in the Blue Mountains are derived from convective storms and consequently do not occur uniformly across the region (Morris, 1934; Mock, 1996; Rorig and Ferguson, 1999). As a result, some watersheds may receive precipitation and/or lightning strikes while others do not during a regionally dry year. Thus, all the conditions necessary for fire may not be satisfied in a single watershed in a given year. However, viewed over a relatively dry decade, the probability of simultaneous occurrence of the conditions necessary for fire in a given year increases, resulting in consistency of fire and precipitation at decadal timescales. These decadal variations in precipitation may be a consequence of variation in the climate of the north Pacific. The influence of the PDO on precipitation in the PNW is similar to that of ENSO and is evident in modern records of snow pack and stream flow (Cayan, 1996; Mantua *et al.*, 1997; Bitz and Battisti, 1999; Cayan *et al.*, 1999; Hamlet and Lettenmeier, 1999) and in historical reconstructions of temperature (Minobe, 1997). Furthermore, there is some evidence that, despite effective fire suppression, decadal variation in twentieth-century fire extent in the PNW may have been influenced by variation in the PDO (Mote *et al.*, 1999).

Fire extent was low during the first several decades of the 1800s in the Blue Mountains, perhaps in response to a reduction in the frequency/intensity of El Niño events that also affected fire regimes elsewhere. Generally, fires in the SW and Patagonia, in South America, varied synchronously because weather in these two regions responds similarly to ENSO (Kitzberger *et al.*, 2001). In contrast, there is some evidence that fires in the SW and PNW varied asynchronously because weather in these two regions responds oppositely to ENSO, as discussed above (Heyerdahl, 1997). However, during the early 1800s, changes in the global climate system reduced the frequency and intensity of El Niño events (Anderson, 1992; Cleaveland *et al.*, 1992; Grissino-Mayer and Swetnam, 2000; Kitzberger *et al.*, 2001). As a consequence, during this remarkable period, fire activity was low in all three regions (Swetnam and Betancourt, 1998; Grissino-Mayer and Swetnam, 2000; Kitzberger *et al.*, 2001).

Non-climatic factors also influenced historical fire regimes

Despite continued variation in climate, fires abruptly ceased in all four watersheds ≈1900, indicating that non-climatic controls currently have a greater influence than climatic ones (Figure 5). Initially, the decline in fire extent coincided with the onset of the wettest period in the 275-year precipitation reconstruction (mid-1880s to 1910s; Figure 5). However, fire extent did not increase again in the 1920s at the outset of the driest period in the record. This unexpected absence of fire was probably not a response to active fire suppression by land-management agencies because these efforts were probably not effective until the 1940s–50s when surplus military aircraft became available (Pyne, 1982). Rather, cattle and sheep grazing may have caused the decline in fire. Grazing reduces the herbaceous fuel that carries low-severity fires in some mixed conifer forests in the PNW (Rummell, 1951; Zimmerman and Neuenschwander, 1984) and grazing has been implicated in the decline of fire occurrence in the SW (Madany and West, 1983; Savage and Swetnam, 1990; Savage, 1991). In the Blue Mountains, Euroamerican settlers increased the number of domestic grazing animals eight- to tenfold in the 1870s–80s and sustained these populations into the mid-twentieth century (Irwin *et al.*, 1994). Consequently, reduced herbaceous fuel loads in the watersheds, or the areas surrounding them, may have persisted well into the twentieth century, lowering the potential for fire ignition and/or spread during the dry years of the 1920s–30s. After this time, active fire suppression was undoubtedly the primary cause of fire exclusion in these watersheds.

Implications of climatic change for future fire regimes

The extent of low-severity fires in the Blue Mountains appears to have been limited historically by fire-season precipitation and snowcover duration while fire occurrence was limited by a relatively low frequency of ignition. These factors are predicted to change as a result of changes in global atmospheric concentrations of greenhouse gases. In particular, the duration of snowcover in the Blue Mountains and elsewhere is expected to shorten in response to an increase in winter and spring temperature (Karl *et al.*, 1993; Brown *et al.*, 1995). Shorter snowcover duration could also result from an increase in the frequency or intensity of ENSO or PDO effects on PNW weather. If summers continue to be dry in the future, a reduction in snowcover duration in the Blue Mountains could increase the length of the fire season and the potential for larger fires. Furthermore, if snow does not cover the watersheds during some winters, lagged relationships between fire and climate could become important. In this case, below-average precipitation in a given year, or period of years, could increase the potential for fire in a subsequent year. Historically, fires did not ignite in the sampled watersheds during every dry year, suggesting that an increase in the frequency or density of lightning strikes could affect future fire regimes in the Blue Mountains. Increased greenhouse gases are predicted to result in increased cloud-to-ground lightning strikes in the extra-tropics without a change in the seasonal distribution of thunderstorms (Price and Rind, 1994). If the density of summer lightning strikes increases across the Blue Mountains, and summer conditions remain conducive to fire ignition and spread, fire frequency could increase.

Given that past climate influenced fire regimes in the Blue Mountains, future climate has the potential to do so as well. However, even if changes in regional climate could be reliably predicted, exact changes in fire regimes are not easily predicted from evidence of the past because dramatic changes in the forest composition, structure and fuel loads since ≈1900 have altered fire-climate relationships. As a result of such uncertainties, predicting actual fire regimes for these forests remains one of the major challenges to predicting future forest conditions.

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