Fire-climate interactions in the American West since 1400 CE

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[1] Despite a strong anthropogenic fingerprint on 20th Century wildland fire activity in the American West, climate remains a main driver. A better understanding of the spatio-temporal variability in fire-climate interactions is therefore crucial for fire management. Here, we present annually resolved, tree-ring based fire records for four regions in the American West that extend back to 1400 CE. In all regions, years with high fire activity were characterized by widespread yet regionally distinct summer droughts. Overall fire activity was high in late Medieval times, when much of the American West was affected by mega-droughts. A distinct decline in fire activity in the late 16th Century corresponds with anomalously low temperatures during the Little Ice Age and a decline in Native American fire use. The high spatiotemporal resolution of our fire record discloses a time-frequency dependent climatic influence on wildfire regimes in the American West that needs to be accounted for in fire models.
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1. Introduction

[2] The extent and severity of wildfires in the American West during the last decade has been remarkable. Since 1998, there have been six years when >2.8 x 10^6 ha burned, more than twice the number of years compared to the previous decade (National Interagency Fire Center, Wildland Fire Statistics, http://www.nifc.gov/fire_info/fire_stats.htm, Boise, Idaho, 2009). The ecological, social, and economic costs of this increase in fire activity have raised awareness of the need for a sustainable forest fire management (USDA National Forest Service, National Fire Plan, http://www.forestsandrangelands.gov/NFP/index.shtml, Washington, D. C., 2000). Despite a strong anthropogenic signature on 20th century fire regimes in western American forests, climate remains a main driver [*Littell et al.*, 2009; *Trouet et al.*, 2006] and a better understanding of regional variation in fire climatology is needed for development of seasonal, annual, or even decadal forecasts of fire activity for fire management planning.

[3] Years of widespread burning in different parts of the American West are generally associated with drought [*Heyerdahl et al.*, 2002; *Swetnam*, 1993; *Taylor et al.*, 2008; *Westerling and Swetnam*, 2003], but drought is not a precondition for widespread burning in all time periods [*Grissino-Mayer and Swetnam*, 2000; *Taylor and Beaty*, 2005]. Preceding wet years often promote burning in dry years by increasing fuel production, but this lagged moisture/fire relationship is more prominent in pine dominated forests with a grass understory in the Southwest (SW) [*Swetnam and Betancourt*, 1990] and the Interior West (IW) [*Veblen et al.*, 2000] than in the Pacific Northwest (PNW) [*Heyerdahl et al.*, 2002] and northern California (NC) [*Taylor et al.*, 2008] (Figure 1). The role of temperature in modulating fire regimes is not restricted to the summer fire season, when temperature influences fire weather conditions [*Trouet et al.*, 2009b], but includes the effect of spring temperature on snowpack duration and fire season length [*Westerling et al.*, 2006]. Temperature influences on wildfire have also been identified on interdecadal to centennial time scales [*Swetnam*, 1993; *Taylor et al.*, 2008] and recent Western fire activity strongly tracks temperature increases since 1985 [*Westerling et al.*, 2006].

[4] The El Niño Southern Oscillation (ENSO) modulates climatic variability in the American West and has been found to affect fire activity both in the pre-suppression period and in the 20th Century [*Gedalof et al.*, 2005]. ENSO teleconnections in the American West display a dipole character that causes a distinct regional effect on fire activity: cold ENSO (La Niña) phases are mainly associated with large fire years in the SW [*Swetnam and Betancourt,* 1990] and in the IW [*Kitzberger et al.*, 2007], and small fire years in the PNW [*Heyerdahl et al.*, 2002, 2008]. Other circulation patterns that impact fire regimes in the American West include the Pacific Decadal Oscillation (PDO) pattern [*Trouet et al.*, 2006], the Pacific North American (PNA) pattern [*Trouet et al.*, 2009b], and the Atlantic Multidecadal Oscillation (AMO) [*Kitzberger et al.*, 2007].

[5] Fire-climate interactions in the American West are thus complex both in space and in time [*Westerling and Swetnam*, 2003] and our understanding and analysis is hampered by the brevity of instrumental records. Recently, broad spatial networks of paleofire records (i.e., tree-rings, charcoal) have become available, providing an opportunity to advance our understanding of the spatial and temporal variability of fire-climate interactions across the American West and on a global scale [*Kitzberger et al.*, 2007; *Marlon et al.*, 2008; *Swetnam and Anderson*, 2008]. Here we contribute to the growing pool of centennial-scale fire-climate studies by developing high-resolution, tree-ring based fire

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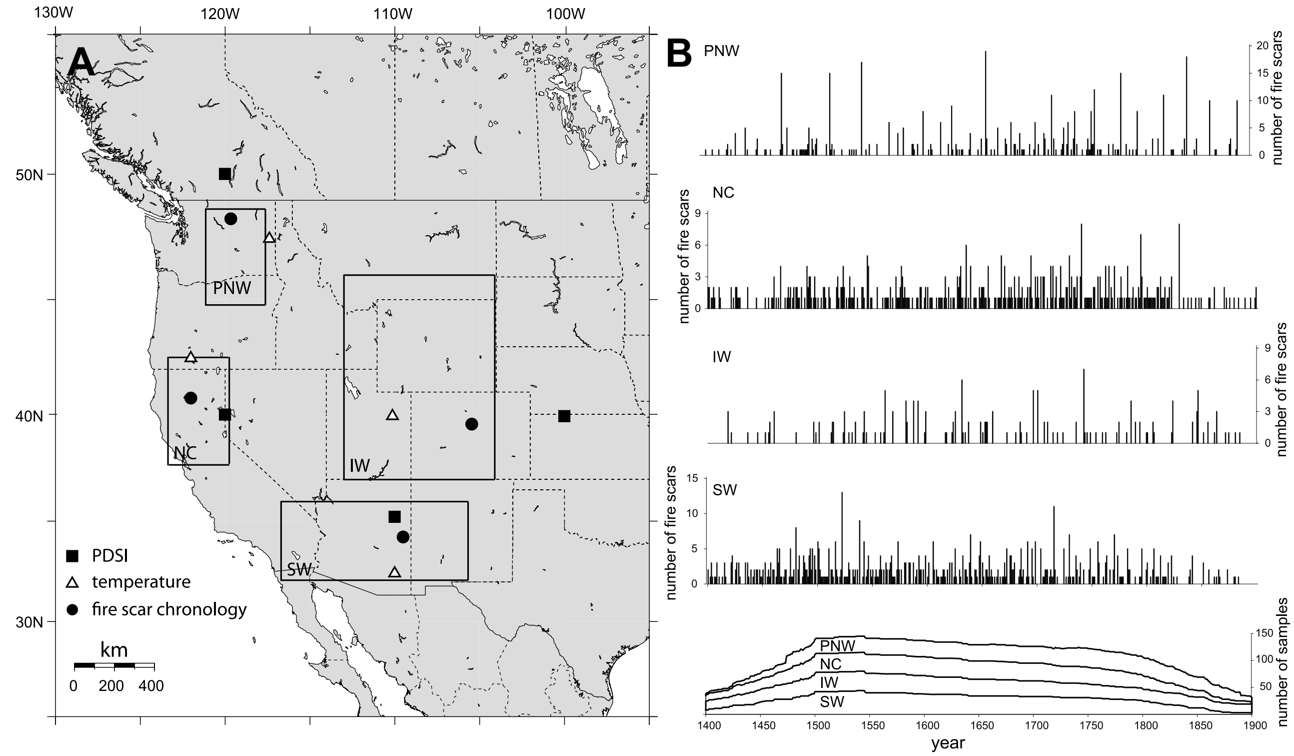

Figure 1. (a) Location (average and outer boundaries of region) of four regional fire-chronologies in the American West and of the corresponding PDSI and temperature reconstruction gridpoints. (b) Time series (1400–1900) and sample depth of the four chronologies.

chronologies for four regions in the American West that reach back to the beginning of the 15th Century.

2. Material and Methods

[6] For each of four regions in the American West (PNW, NC, IW, and SW), we have selected fire-scar records from individual trees that were recording fire prior to the year 1500 (Figure 1a and Table S1).[1] For the PNW, the IW, and the SW, fire-scar records were selected from the International Multiproxy Paleofire Database (IMPD; http://www.ncdc.noaa.gov/paleo/impd/paleofire.html). A database developed as part of a USDI/USDA Interagency Joint Fire Sciences Program project [*Taylor et al.*, 2007] and containing 2980 fire scarred trees from 350 sites in Baja California, California, and Oregon, provided fire-scar records for NC and for the Californian part of SW. Fire records from individual trees were compiled per region to develop regional fire scar chronologies (Table 1). Annual fire indices per region were calculated as the percentage of samples that recorded a fire in each year [*Taylor et al.*, 2008]. Annual fire synchrony between two regions was identified by calculating over a centered 50-year period the number of fire years recorded in both regions divided by the number of fire years recorded in either region. Total fire synchrony between the four regions was then calculated as the sum of fire synchronies for all possible combinations [*Swetnam*, 1993].

[7] Regional fire chronologies were compared to gridded reconstructions of summer Palmer Drought Severity Index (PDSI) for the American West (1000–2003 [*Cook et al.*, 2004]) and to 5° × 5° gridded annual temperature reconstructions (1500–1980 (E. R. Wahl et al., manuscript in preparation, 2010)) averaged in blocks corresponding most closely to the spatial definitions of the regional fire records (Figure 1a). Relations between the fire records and ENSO were examined based on a reconstruction of the Niño3 index (1408–1978 [*Cook*, 2000]).

[8] Superposed Epoch Analysis (SEA) was used to evaluate the relationship between events (fire years) and climate (PDSI, temperature, ENSO) by superposing a window of contemporaneous and lagged annual climatic conditions over each fire year [*Baisan and Swetnam*, 1990; *Haurwitz and Brier*, 1981]. SEA was performed for fire years when at least 10% of samples were scarred (minimum of two samples) and for non-fire years. Significance levels were determined from bootstrapped confidence interval estimates (95% and 99%) based on Monte Carlo simulations [*Mooney and Duval*, 1993]. Decadal-scale relationships were identified based on Pearson correlation coefficients calculated for fire synchrony and climate time series (1464–1834) of sequential 50-year non-overlapping means (n = 8 [*Swetnam*, 1993]).

3. Results

[9] The four fire chronologies recorded fires back to at least 1440 (Table 1 and Figure 1b) and 145 trees were recording fires by the early 1500s. *Pinus ponderosa* was the primary recording species. Widespread burning (≥10% scarred) was frequent in all regions, but less so in the IW

[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL041695.

Table 1. Characteristics of the Fire Scar Chronologies for Each Region in the American West[a]

Region	Species	Elevation (m)	Trees	Total Fire Scars	Average CFI[b] (years)	Period of Record (10 Recording Trees)
PNW	Pipo (96%)	1433 (825–1650)	66	437	6.2	1441–1910
NC	Pipo (36%) Psme (21%) Cade (14%)	1630 (700–2430)	36	471	4.2	1400–1861
IW	Pipo (76%)	2450 (1255–3400)	81	192	11.2	1281–1974
SW	Pipo (81%)	2280 (1720–3050)	51	646	2.8	1403–1859

[a]Regions are PNW, Pacific Northwest; NC, Northern California; IW, Interior West; and SW, Southwest. Species are Pipo, *Pinus ponderosa*; Psme, *Pseudotsuga menziesii*; and Cade, *Calocedrus decurrens*.
[b]CFI is composite fire interval (≥10% of trees scarred).

(composite fire interval (CFI) = 11 years) than in the other regions (CFI = 3–6 years).

[10] Fire years in all regions were characterized by widespread but regionally distinct summer drought (Figure 2a), but there was no influence of antecedent climate on years with widespread burning (Figure 2b). In contrast, non-fire years in all regions were associated ($P < 0.05$) with moist conditions. Interannual temperature variations did not influence fire occurrence in any of the regions ($P > 0.05$).

[11] ENSO had a strong influence on burning in the SW. Years with widespread burning were associated with La Niña (negative ENSO) conditions that were preceded by El Niño years (Figure 2b) and non-fire years were associated with these El Niño years ($P < 0.05$). Of the 10% largest fire years in the SW (n = 42), 76% occurred in La Niña years. Concurrent, anomalous ENSO conditions were not associated ($P > 0.05$) with fire years in other regions.

[12] Widespread fires were most frequent in the 1400s and the 1700s and their occurrence was reduced from approximately 1500 to 1650 AD (Figure 3b). Fire activity was at its lowest from 1550 to 1600 AD. This decrease is evident in each region except for the IW. Fire synchrony among the four regions peaked during the period of reduced fire activity (ca. 1575–1610 AD), a second peak occurred around 1675–1725 AD, and a third one around 1830 AD (Figure 3a). Periods of high fire synchrony across the American West corresponded to reconstructed periods of low temperature across the Northern Hemisphere (NH; $r = 0.69$; $p < 0.1$), but not to reconstructed PDSI over the study area ($r = -0.2$; $p > 0.1$).

4. Discussion

[13] We examined the climatic drivers of wildfire activity over broad spatial and long temporal scales with annually resolved records of fire activity. Our work emphasizes the spatial and temporal limits of tree-ring based paleofire reconstruction in the American West by selecting only individual trees that recorded fire prior to 1500. These samples are rare and they were compiled from widely dispersed sites in each region. The influence of local controls on fire activity as well as of stochasticity in the fire signal is reduced when a fire record is compiled from broadly distributed, independent sites [*Swetnam and Betancourt*, 1990,

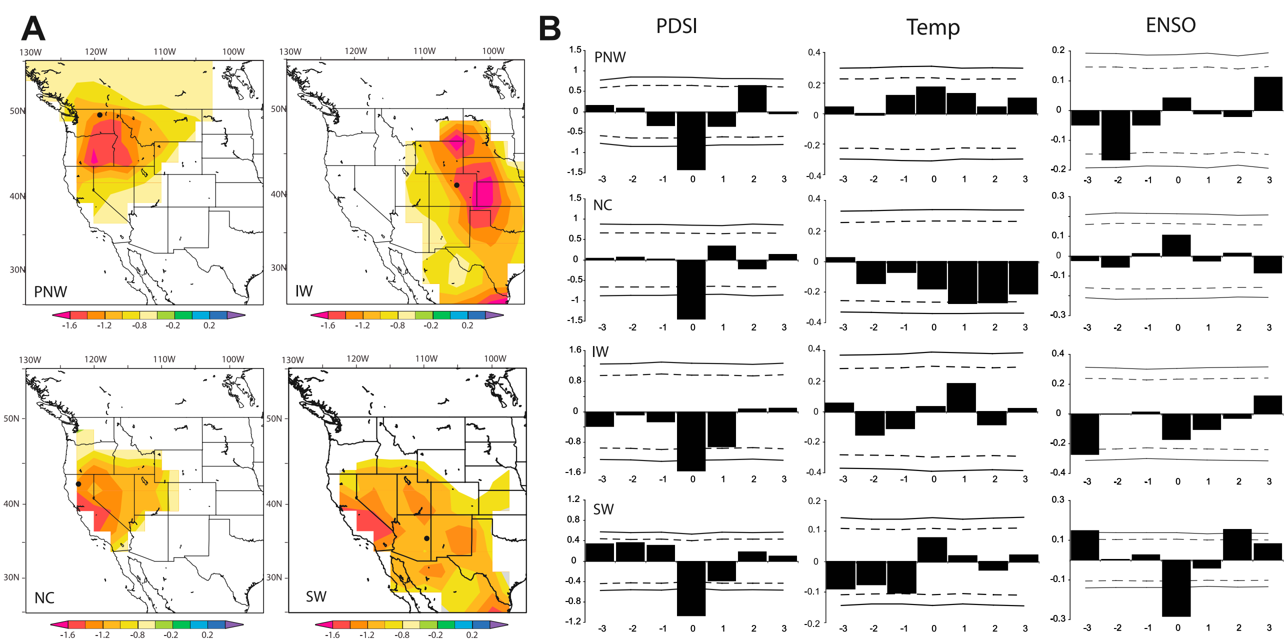

Figure 2. (a) Composite maps of gridded summer PDSI [*Cook et al.*, 2004] during fire years (more than 10% of the trees scarred; 15% for SW) in four regions of the American West. (b) SEA of the four fire-chronologies with contemporaneous and lagged (three years prior to three years following) indices for PDSI, temperature, and ENSO. Significance levels are indicated as dashed (95%) and full (99%) horizontal lines. Composite maps were produced using the KNMI climate explorer (http://climexp.knmi.nl [*van Oldenborgh and Burgers*, 2005]).

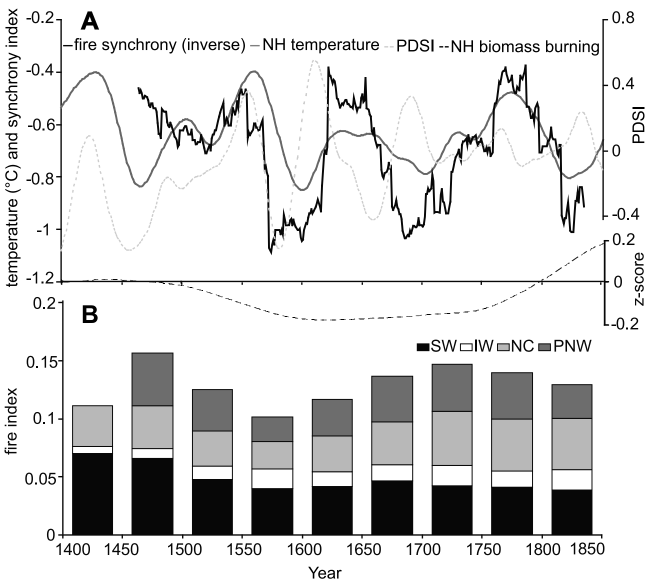

Figure 3. (a) Reconstruction of fire synchrony (50-year running sums), NH temperature [*D'Arrigo et al.*, 2006], summer PDSI (average over 30–50N and 105–125W [*Cook et al.*, 2004]), and NH biomass burning (10-year smoothing spline [*Marlon et al.*, 2008]). Deviations from the 1961–1990 average and 50-year smoothing splines were calculated for the temperature and PDSI time series. Fire synchrony values are inversed for visual purposes. (b) Average (50-year) fire index for four regions in the American West. Fire index values, based on a minimum of 10 recording trees, were calculated only from 1441 onwards for the PNW, and no average value was calculated for the period 1400–1450 for this region.

1998]. Fire event synchrony on such large spatial scales is mostly driven by top-down controls [*Gedalof et al.*, 2005] and is a strong indicator of climatic influence on fire regimes [*Swetnam and Anderson*, 2008].

[14] Two characteristics of the resulting fire chronologies indicate that they reflect regional fire regimes despite relatively low sample replication. Firstly, the composite return intervals for widespread burning in each region fall within the range of fire return intervals found in the literature for the same types of forest: 2–16 years in the PNW [*Heyerdahl et al.*, 2008], 3.4–9.4 years in NC [*Taylor and Beaty*, 2005], 8–22 years in the IW [*Veblen et al.*, 2000], and 2–5 years in the SW [*Grissino-Mayer and Swetnam*, 2000]. Secondly, synchronized fire activity in all regions, as recorded by the regional fire chronologies, was strongly related to drought in the year of fire. A spatial composite analysis indicated that widespread fires were induced by regionally distinct summer drought conditions (Figure 2). The strength of the fire-drought relationship can be interpreted as a validation not only for our fire chronologies, but also for Cook's (2004) spatial drought reconstruction.

[15] We did not find an influence of interannual temperature variability on fire activity, but fire-climate interactions have previously been identified as time-frequency dependent. Whereas precipitation variability is responsible for high-frequency changes in fuel moisture, decadal-to-centennial scale temperature variations can induce shifts in vegetation, fuel type, and distribution [*Kelly and Goulden*, 2008; *Swetnam*, 1993; *Taylor et al.*, 2008].

[16] The long fire-scar records from individual trees provide information on interannual variability in fire for the American West since 1400. Annually resolved fire records that date back to Medieval times are rare, with the notable exception of Swetnam's (1993) 2000-year long record of fires preserved in Giant Sequoia (*Sequoiadendron gigantea*) trees in the Sierra Nevada. Like *Swetnam* (1993), we found high fire activity in the Medieval period (previous to 1500), when large parts of the American West experienced mega-droughts [*Cook et al.*, 2004]. The global reorganization of the climatic system that took place during this Medieval Climate Anomaly (MCA) [*Trouet et al.*, 2009a] included prolonged La Niña like conditions [*Graham et al.*, 2007] that might explain why fire activity during the MCA was strongest in the ENSO-sensitive SW. The mechanisms for 21st Century warming are different from those driving the MCA, but the relationship between temperature and fire activity during this earlier period suggests that fire activity in the American West will increase with projected multi-decadal warming.

[17] The fire record across the American West shows a distinct decline in fire activity in the late 16th Century, and this decline is consistent with an independent record of global and northern hemisphere biomass burning [*Marlon et al.*, 2008] and a reduction in pyrogenic methane emissions [*Ferretti et al.*, 2005]. One explanation for this decrease would be strongly declining temperatures during this period that constitute the core of the cool period (ca. 1500–1800) generally known as the Little Ice Age (LIA [*Grove*, 1988]) and that is represented in each of the fire regions. The PNW and NC in particular exhibit their largest declines over the entire 1500–1980 reconstruction period. This is supported by the strong correspondence during this period between decadal-scale temperature fluctuations and region-wide fire synchrony across the American West. During cold decades, fire frequencies are lower, resulting in increased fuel accumulation and more widespread fires. The coarse-grain spatial pattern of fuel distribution resulting from these widespread fires [*Swetnam*, 1993] can induce a high degree of fire synchrony across different regions.

[18] Broad-scale fire synchrony can also be related to synoptic-scale circulation patterns. We find a period of enhanced fire synchrony from 1660–1710 AD, which coincides with a long warm phase of the Atlantic Multidecadal Oscillation (AMO [*Gray et al.*, 2004]). Another period of positive values in the AMO reconstruction (approx. 1580–1600 AD) also coincides with increased fire synchrony in our fire record. AMO-related North Atlantic Ocean warming induces multidecadal drought conditions over the American West [*McCabe et al.*, 2004] and our results support *Kitzberger et al.*'s [2007] interpretation that low time-frequency AMO-modulation influences western forest fire regimes.

[19] A decline in the Native American population in the 16th Century due to the introduction of diseases by European explorers [*Denevan*, 1992] cannot be ruled out as an explanation for the 16th Century decrease in fire activity [*Ferretti et al.*, 2005]. It must be noted, however, that Native American fire use was generally very localized and unpre-

dictable [*Barrett et al.*, 2005] and is thus unlikely to have caused synchronous, regional-scale burns.

5. Conclusion

[20] The long (420+ years) annually resolved fire record exhibits a distinct time-frequency dependence in fire activity in the American West that is related to climate variability. Interannual variability in summer drought is the main driver of fire variability in all four studied regions, but decadal-to-centennial-scale fire activity is more strongly related to low-frequency variations in temperature. Time- frequency dependent fire-climate interactions as well as the spatial expression of atmospheric circulation patterns on fire activity should be considered in models that assess and project the response of fire regimes to anthropogenic climatic change.

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