Socioecological transitions trigger fire regime shifts and modulate fire–climate interactions in the Sierra Nevada, USA, 1600–2015 CE

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Large wildfires in California cause significant socioecological impacts, and half of the federal funds for fire suppression are spent each year in California. Future fire activity is projected to increase with climate change, but predictions are uncertain because humans can modulate or even override climatic effects on fire activity. Here we test the hypothesis that changes in socioecological systems from the Native American to the current period drove shifts in fire activity and modulated fire–climate relationships in the Sierra Nevada. We developed a 415-y record (1600–2015 CE) of fire activity by merging a tree-ring–based record of Sierra Nevada fire history with a 20th-century record based on annual area burned. Large shifts in the fire record corresponded with socioecological change, and not climate change, and socioecological conditions amplified and buffered fire response to climate. Fire activity was highest and fire–climate relationships were strongest after Native American depopulation—following mission establishment (ca. 1775 CE)—reduced the self-limiting effect of Native American burns on fire spread. With the Gold Rush and Euro-American settlement (ca. 1865 CE), fire activity declined, and the strong multidecadal relationship between temperature and fire decayed and then disappeared after implementation of fire suppression (ca. 1904 CE). The amplification and buffering of fire–climate relationships by humans underscores the need for parameterizing thresholds of human- vs. climate-driven fire activity to improve the skill and value of fire–climate models for addressing the increasing fire risk in California.

anthropogenic landscapes | fire ecology | land use | regime shifts | climate variability

An increase in the extent of forest fires in the American West since the mid-1980s (1) has enhanced risks to lives, property, water quality, biodiversity, carbon sequestration, and other ecosystem services (2). This increasing wildfire trend has become even steeper during the past decade, with a higher number of large wildfires (>100 km^2) each year in each Western state compared with the annual average from 1980 to 2000 (3). The fire problem is particularly acute in California, where a history of fire suppression (4), climate change (1, 5), more extreme fire weather (6), expanding development (7), and massive wildfires (e.g., 2013 Rim Fire, 1,042 km^2) have caused significant socioecological impacts. Future area burned in California is projected to further increase with anthropogenic warming (8). With more than half of the annual federal firefighting budget already being spent suppressing fires in California (4), a sustainable system of fire management requires approaches beyond active fire suppression (9). Predicting future fire activity is challenging because humans can alter fire regimes and fire–climate relationships even if climate becomes more conducive to fire (10). Changes in socioecological systems (SESs) can modulate or even override climatic effects on fire regimes through changing land use, ignitions, fuel conditions, or fire suppression (11). Our understanding of the mechanisms and effects of humans on fire regimes and fire–climate interactions is limited and can be counterintuitive (12). It is the foundation for the development of effective strategies to address the amplified fire effects expected with a warming climate.

Insights into the mechanisms and effects of humans on fire regimes and fire–climate relationships can be gained by examining the response of fire to transitions in SESs (12). Here we test the hypothesis that transitions in SES from the Native American to the current period in California's Sierra Nevada drove shifts in lower montane forest fire regimes and modulated fire–climate relationships.

For this purpose, we developed a four-century-long index of fire activity that is based on the merging of fire dates preserved in 1,948 wood samples from 29 lower montane forest sites along the extent of the Sierra Nevada (>500 km; Fig. 1) with a 20th-century fire index based on records of annual area burned (*Methods*). We then compared our fire record to proxy records of temperature and moisture and to documentary records of change in SES. Theory (13), modeling (14), and empirical studies (15) demonstrate that fire regimes and fire–climate relationships in these forests are sensitive to fire–fuel interactions. If changes in SES significantly altered fire–fuel interactions, (*i*) Native American depopulation in the late 18th century would lead to an increase in widespread fire activity and strengthened fire–climate relationships as a result of increased fuel continuity and (*ii*) fire activity and strength of the fire–climate relationships would decline with rapid mid-19th-century European settlement and expansion of grazing, logging, and road building that reduced fuel continuity. Fire activity would further continue to decline into the 20th century despite an increase in fuels as a result of fire suppression.

Significance

Twenty-first–century climate change is projected to increase fire activity in California, but predictions are uncertain because humans can amplify or buffer fire–climate relationships. We combined a tree-ring–based fire history with 20th-century area burned data to show that large fire regime shifts during the past 415 y corresponded with socioecological change, and not climate variability. Climate amplified large-scale fire activity after Native American depopulation reduced the buffering effect of Native American burns on fire spread. Later Euro-American settlement and fire suppression buffered fire activity from long-term temperature increases. Our findings highlight a need to enhance our understanding of human–fire interactions to improve the skill of future projections of fire driven by climate change.

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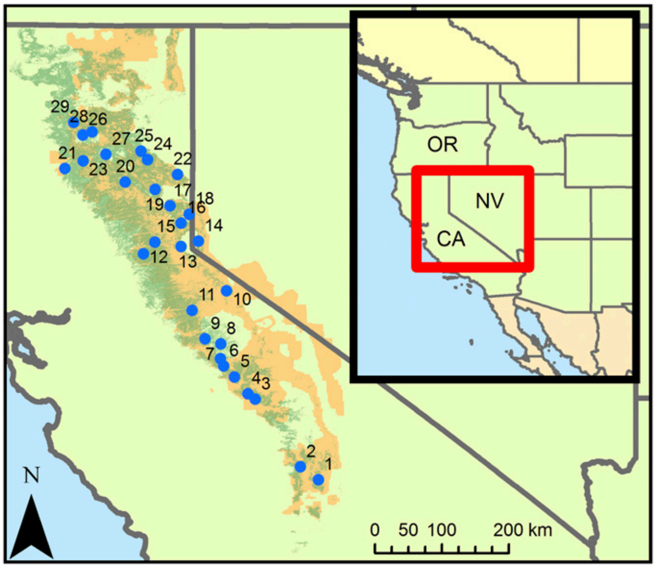

Fig. 1. Location of fire scar collection sites in lower montane forests (green shading) in the Sierra Nevada ecosystem (yellow shading). Information on site characteristics and collections are given for corresponding numbers in Table S1.

Fire was frequent during the past four centuries at the 29 lower montane forest sites, and the mean and median intervals between fires in a wood sample were 17.7 y and 13.5 y, respectively (Fig. 1 and Table S1). Interannual and multidecadal variability in fire activity was evident over the 1600–2015 CE period (Fig. 2).

We used regime-shift analysis to identify four fire-regime periods in Sierra Nevada lower montane forests (1600–1775 CE, 1776–1865 CE, 1866–1903 CE, and 1904–2015 CE) that were separated by three fire-regime shifts (Fig. 2 and Table 1). The timing of the fire regime shifts was not influenced by decreasing sample depth through time (Fig. 2 and Fig. S1). The first shift occurred in 1776, the resulting fire regime persisted for 90 y, and the mean fire index over this period was nearly twice that of the preceding 175 y. After the second shift, in 1866, the fire index returned to pre-1776 levels, a condition that persisted for 38 y. The third shift persisted until the present and had a fire index four to eightfold lower than in any other fire regime period. A regime-shift analysis for the post-1900 fire regime using a shorter window shows a shift in 1962 to a period with a 50% reduction in the fire index and a shift in 1987 to a higher fire index and the highest since 1900 (Fig. 2). Regime shifts in the Sierra Nevada fire index were not coincident with regime shifts in temperature, moisture, or other climate patterns, except for the increase in temperature since the late 1980s (Fig. 2 and Fig. S2). The four fire-regime periods show a striking correspondence to periods with different SESs that can influence fire (Table 1). Native American fire management prevailed until establishment and expansion of agrarian-based Spanish missions starting in 1769, after which the Native American population declined (16) (Fig. 3). Sierra Nevada tribes were hunter-gatherers who used sophisticated burning practices to manage resources (17). The fire index nearly doubled with the transition to the Spanish–Mexican Period (1769–1847 CE; $P < 0.05$; Fig. 3 and Table 1). In 1848, a rapid influx of European immigrants occurred after gold was discovered in California (i.e., Gold Rush) (18). The average fire index during the Gold Rush–Settlement period (1848–1904 CE) was similar to that during the Native American period ($P > 0.05$), and the population of California increased from ~93,000 to nearly 1.5×10^6 people by 1900 (19) (Table 1 and Fig. 3). A policy of suppressing fire was implemented on federal forest lands in the early 20th century (4), which reduced fire activity and increased fuels except in areas designated for "natural" fire management in recent decades (15). The fire index, on average, was four to eightfold lower ($P < 0.05$) under fire suppression than under any other SES, and the human population of California increased to more than 39×10^6 by the end of 2015 (19) (Fig. 3 and Table 1).

Fire activity in each fire regime period was influenced by interannual climate variability (Figs. S3 and S4). More (less) fire occurred in dry (wet) and warm (cool) years, and high-fire years were preceded by moist and sometimes cool conditions 1–4 y earlier.

However, fire–climate relationships were modulated by SES. There was a strengthening of the interannual fire–moisture relationship during the Spanish–Mexican period that coincides with the 1776 fire-regime shift to a period when the average fire index nearly doubled (Table 1 and Fig. 3). The fire–moisture relationship weakened between 1865 and 1910 and after 1950, and the weakening coincided with the end of the Gold Rush followed by implementation of fire suppression. SES also modulated fire–climate relationships on multidecadal time scales. The average 20-y fire index strongly tracked temperature ($r > 0.7$, $P < 0.01$) until 1860, at which time the association weakened ($r = 0.3$, $P < 0.05$) and then decreased to less than the threshold for statistical significance at the turn of the 20th century (Fig. 4). The erosion of the multidecadal fire–temperature relationship coincides with the end of the Gold Rush and then the onset of fire suppression.

Sierra Nevada fire regimes were thus strongly influenced by climate and SES during the past four centuries. Years with widespread burning were characteristically dry and warm, and antecedent climate was also important (Figs. S3 and S4). Fine fuel production in wet/cool years promotes widespread burning in more continuous fuels in subsequent drought years, a common pattern observed in other semiarid pine-forest ecosystems in the American West (20–22) and other steppe and savanna ecosystems that experience high-frequency climate variability like the Sierra Nevada (23). Fire activity was also stronger (weaker) in warmer (cooler) decades, and the fire index closely tracked temperature until 1860. As the region came out of the Little Ice Age (ca. 1500–1850 CE) and temperatures increased from 1600 onward, the fire index was also increasing (Fig. 4). The fire–temperature relationship decays in the period after 1860 and then disappears with widespread Euro-American settlement and fire suppression in the early 20th century. Sierra Nevada fire activity should have increased with 20th-century warming. The expected fire index since 1900, using the pre-1860 20-y average fire index and temperature relationship ($r^2_{\mathrm{adj}} = 0.64$; n = 13; $P < 0.006$), exceeds or is close to the peak fire index in the late 18th and mid-19th century (Fig. 4). The 20th-century fire index, instead, has been lower than in any other period in the 415-y fire record, thus exemplifying the 20th century "fire deficit" identified for the American West (24). Our work further supports earlier findings that fire activity and biomass burning in the Western United States track low-frequency temperature variation during the past two millennia (25, 26) until the early to mid-19th century, when human activity disrupted fire–climate relationships. The overall sensitivity of fire regimes to low-frequency temperature variation is related to temperature-driven vegetation changes that alter fuel structure and fuel type (26, 27). The record of biomass burning across the Western United States shows that burning peaked in the mid to late-19th century, with the peak being attributed to expanding settlement and increased burning from land clearance and slash fires associated with logging (24). The peak we find in Sierra Nevada-specific fire activity, in contrast, occurs earlier in the early 19th century and is associated with a decline in Native American small-patch burning that had reduced potential for fire spread.

Despite the strong influence of climate variability on Sierra Nevada fire activity, fire-regime shifts coincided with transitions in SES and not shifts in climate. The fire regime shift in 1776 from Native American fire management to a period with a nearly

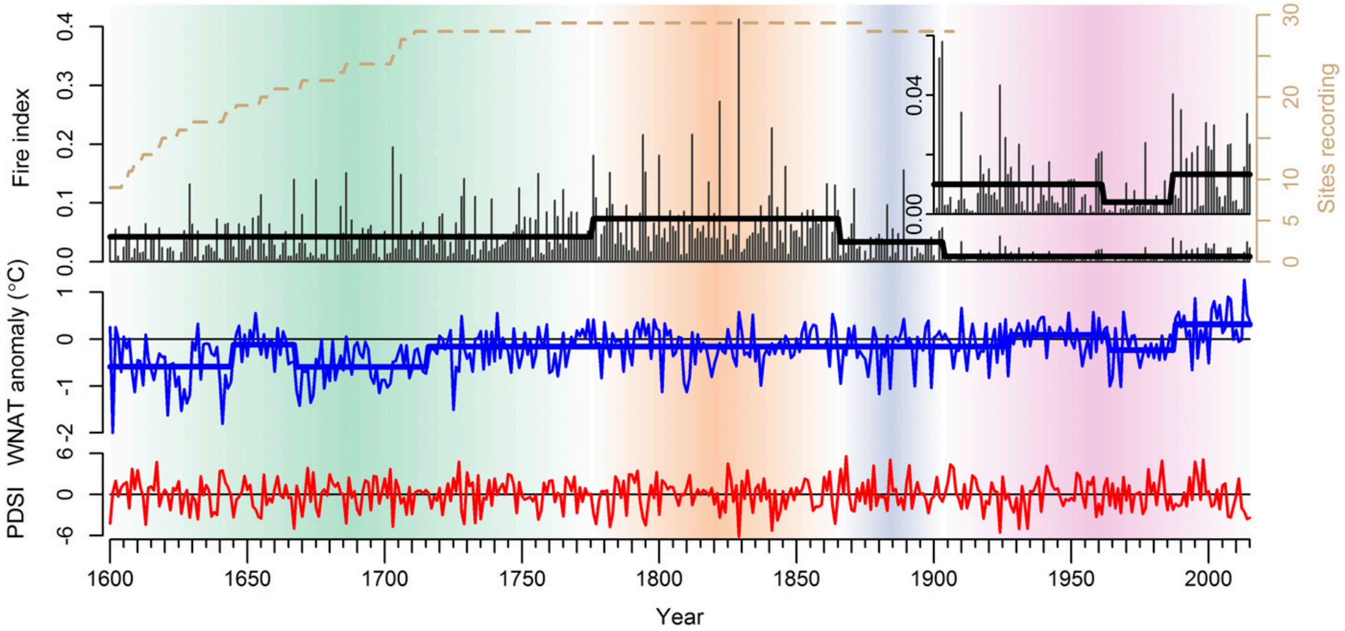

Fig. 2. Regime shifts in time series (1600–2015 CE) of Sierra Nevada fire index, summer moisture (i.e., PDSI) (60), and summer temperature (i.e., WNAT) (59). A switch to a new regime (fire or climate) is shown by a vertical line. The change point ($P < 0.05$) was identified by using a 30-y window following Rodionov (58). A 15-y window and change point of $P < 0.1$ was used for the inset period (1900 to present). The number of tree-ring sites recording fires in each year for the 1600–1907 CE period is shown by the dashed line. The fire regime periods are indicated by color shading: 1600–1775 CE (green), 1776–1865 CE (orange), 1866–1903 CE (blue), and 1904 CE to present (pink).

a doubled fire index coincides closely with the date of Native American contact with Spanish missionaries in 1769 (16). Spread of nonnative diseases to Native American populations in and near the missions began almost immediately, and records show a rapid decline in the Native American population from disease in the late 18th and early 19th century (16). Ethnographic references to the "black death" in Sierra Nevada tribes suggest that disease spread quickly via trails and trade routes between the coast, central valley, and Sierra Nevada (28, 29). Half the estimated Native American population in California in 1769 had disappeared by 1845 (16). The influx of migrants to California during the Gold Rush (1848–1855 CE) (18) accelerated Native American depopulation from disease, dislocation, mistreatment, and even state-sanctioned violence (30), and, by 1855, only 15% of the Native American population present in 1769 remained (16). Approximately 10% of the Native Americans in California belonged to ethnographic groups that included territories within Sierra Nevada lower montane forest (31). Native Americans who used lower montane forest habitat used fire extensively to enhance productivity of wild tree crops, shrubs, grasses, tubers, roots, and game, and to reduce fuels. Burning is thus considered to have been a core management practice for sustaining resource diversity (17, 32, 33). The scale of the effects of Sierra Nevada Native American burning is disputed (17, 34), but augmented ignitions would reduce fuels and fuel continuity across forest landscapes. Fire in Sierra Nevada lower montane forests is regulated by the dynamics of the burn-patch mosaic (15, 35). Burn patches constrain fire spread until sufficient fuels build up in a burned patch so it can burn again. A reduction in the frequency of small-patch burning by Native Americans would reduce fuel patch heterogeneity and diminish the self-limiting effect of burns on subsequent fires. In addition to this, in 1793 the Spanish Governor officially prohibited the use of fire in a proclamation to protect forage for livestock (36). Fuels would become more continuous as depopulation progressed, thus increasing potential for larger burns, and promoting a shift from a more fuel-limited

Table 1. Fire index and climate in Sierra Nevada lower montane forests in the fire regime periods identified by the regime shift analysis and in socioecological periods identified in documentary records

Fire regime period	Fire index	PDSI index	WNAT anomaly, °C
1600–1775	0.042 ± 0.036*	0.054 ± 2.081†	−0.392 ± 0.470†
1776–1865	0.073 ± 0.064†	−0.126 ± 2.208†	−0.133 ± 0.374*
1866–1903	0.034 ± 0.033*	0.272 ± 2.171†	−0.185 ± 0.422*
1904–2015	0.009 ± 0.009‡	−0.052 ± 2.227†	0.031 ± 0.420‡
Land use period			
Presettlement	0.042 ± 0.037*	0.051 ± 2.100†	−0.412 ± 0.468†
Spanish-Colonial	0.072 ± 0.067†	−0.138 ± 2.219†	−0.139 ± 0.379$^{\dagger *}$
Gold Rush–Settlement	0.043 ± 0.037*	0.189 ± 2.078†	−0.129 ± 0.392*
Fire Suppression	0.009 ± 0.010‡	−0.053 ± 2.237†	0.030 ± 0.422‡

Values are presented as mean ± SD. The climate variables were summer moisture (PDSI) (60), and summer temperature (WNAT) (59). Means in a column with different symbols (*,†,‡) were significantly different ($P < 0.05$) as determined using ANOVA and Tukey's post hoc tests. Presettlement, 1600–1768 CE; Spanish Colonial, 1769–1847 CE; Gold Rush–Settlement, 1848–1904 CE; Fire Suppression, 1905–2015 CE.

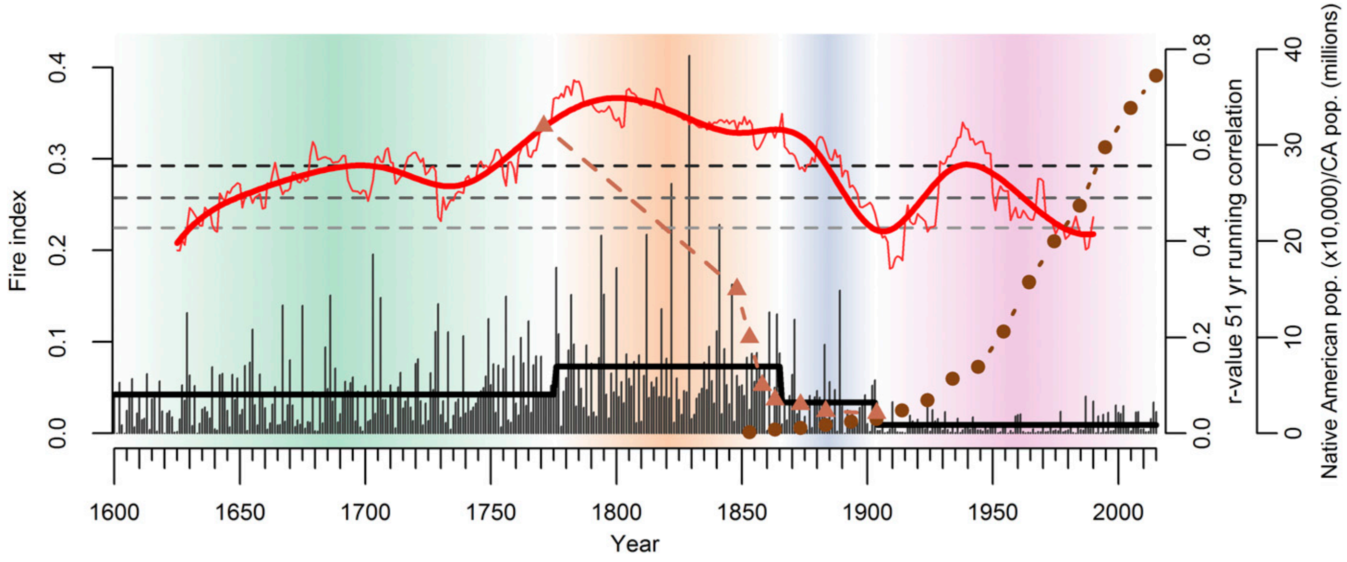

Fig. 3. Variation in strength of fire–moisture (60) relationships (i.e., PDSI) and population size of Native Americans (16) (triangle) and others (19) (circles) in California. The fire regime periods are indicated by shading as in Fig. 2. The *r*-values are 51-y running Pearson product-moment correlation coefficients of PDSI (inverted for presentation) and fire index is plotted on the 26th year of the window. Statistical significance ($P < 0.05$, $P < 0.01$, $P < 0.001$) is shown by increasingly dark dashed lines.

to a climate-limited fire regime. The doubling of the fire index and its amplified sensitivity to interannual moisture variability after 1776 are both consistent with the decline in Native American burning as the primary cause of the late 18th century fire-regime shift.

In contrast, land use change associated with the Gold Rush/Euro-American settlement period reduced fuel continuity and potential fire spread, leading to lower fire activity and less strong fire–climate relationships. Livestock was imported from neighboring states, and local production was significantly increased to feed the growing human population. In 1862, there were 3×10^6 sheep in California, and numbers increased to 6×10^6 head by 1876 (37). During the 1860s and 1870s, shepherds led a seasonal migration of large herds of sheep in the central valley through forests into alpine meadows in the Sierra Nevada to access forage. Written accounts of grazing effects from this period indicate that grazing was very intense, caused soil erosion, and made travel through the Sierra Nevada with saddle and pack animals difficult because of a lack of grass forage, and these effects were noted in vegetation types across the entire Sierra Nevada range (38). Thus, Sierra Nevada changes in the SES are implicated as the trigger for the 1866 fire-regime shift to lower fire activity via fuel fragmentation caused by livestock grazing. Livestock grazing has been implicated in similar fire-regime shifts in other montane pine forests in the American West (39), Mexico (40), and Mongolia (41). In contrast, the effect of logging activity on fuels or ignitions in lower montane forests during this period was spatially limited to population centers and transportation corridors (38).

The fire-regime shift to a period of low fire activity in 1904 was caused by establishment of a fire suppression policy on federal forest lands (4). Fire suppression has been very effective as illustrated by the lowest (five to eightfold lower) average fire index during the past four centuries. Changes in fuels and fire-suppression tactics also modulated fire–climate relationships between 1900 and 2015. Early in the period, when fuel levels were low, suppression weakened the fire–moisture relationship, but moisture influences strengthened in the 1940s when suppression became less effective and people were diverted from firefighting to the military in WWII (42). The weakened post-WWII fire response to climate is related in part to the use of considerable surplus military equipment, including introduction of aerial fire detection that reduced time to initial attack and more effective suppression (42). Stronger fire–climate relationships have developed since the mid-1980s, and our analysis, and other studies, show that fire activity, particularly at high severity (43), has increased as a result of warming and earlier spring snowmelt (1).

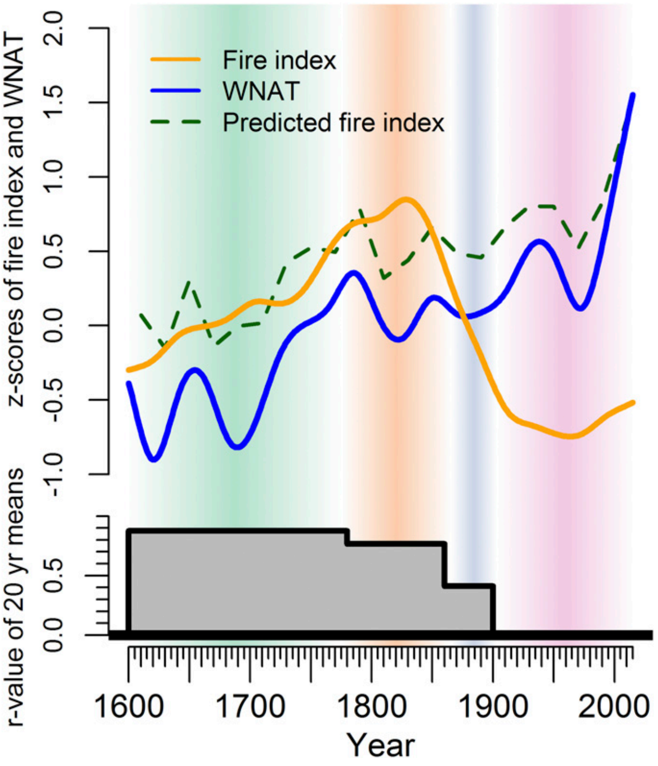

Fig. 4. Interdecadal variation in mean 20-y nonoverlapping periods of summer temperature (i.e., WNAT) (59) and fire index, correlation between fire index and WNAT (gray fill), and predicted fire index from 20-y mean temperature (dashed). Values were smoothed with a 20-y cubic spline for presentation. The fire-regime periods are indicated by shading as in Fig. 2.

High accumulations of surface and canopy fuels from fire suppression are important contributors to the recent strengthening of fire–climate relationships and to higher-severity fire (43). Most Sierra Nevada lower montane forests have not burned in more than a century (44). High fuel loads and a warmer climate reduce success of initial attack in combination with severe fire weather, rough terrain, or simultaneous lightning ignitions over large areas (45). When initial attack fails, fires spread rapidly and become large with large areas of canopy-killing fires that are historically unusual (46). Accumulating evidence indicates that the increase in area of canopy-killing fires is initiating a persistent vegetation switch from forest to fire-dependent shrub lands over large areas that is maintained by positive feedbacks between shrub lands and repeat high-severity fire (47, 48).

The hypothesis that historic changes in SES would control Sierra Nevada fire activity and modulate fire–climate relationships is supported by our analysis. Interannual climate variability influenced fire activity over the entire record of fire, but humans constrained the fire–climate relationship through socioecological processes that affected fire–fuel–climate interactions. The Sierra Nevada fire index nearly doubled with the demise of Native American fire management and became very strongly driven by interannual variation in moisture as fuels became more continuous. The strong fire activity and fire-climate response to Native American depopulation supports a perspective of widespread Native American influence on vegetation and other resources in the Sierra Nevada by fire use (33). Our results also run counter to Ruddiman's (49, 50) "early Anthropocene" hypothesis that widespread pandemics (including in the Americas in the period 1500–1750 CE) led to reforestation of abandoned land, increased carbon sequestration in growing forests, and a short-term atmospheric CO_2 decrease of 4–10 ppm (51). Emissions from increased Sierra Nevada fire activity associated with Native American depopulation may have, to a limited extent, counterbalanced a pandemic-induced atmospheric CO_2 decrease from forest regrowth. In fact, this case suggests relationships between pandemics, traditional people, and carbon are more complex and variable.

Shifts to lower fire activity and weaker fire–climate relationships accompanied periods when livestock was introduced and fires were actively suppressed. This effect was most evident at multidecadal and centennial time scales. The strong multidecadal fire–temperature relationship before widespread Euro-American settlement in the mid-19th century decreased to less than the threshold for statistical significance after fire suppression caused a strong reduction in fire activity after 1900.

Fire regimes in other western semiarid pine forests have responded in diverse ways to transitions in SES before the fire suppression period. In Colorado, fire activity did not change until the mid- to late 19th century with widespread Euro-American settlement (22), and it increased rather than decreased, as in the Sierra Nevada. In the early to mid-17th century, fire extent increased when Spanish missions were established in the American Southwest (52) and in Northwestern Mexico in the late 18th century when missions were abandoned (40). As in the Sierra Nevada, reduced Native American burning and increased fuels are implicated in the fire-regime shifts. However, different timing of SES transitions initiated earlier or later fire-regime shifts. Subregional differences in the timing and direction of fire-regime shifts in semiarid western pine forests driven by variation in SES transitions underscores the critical need to develop more nuanced representations of human–fire interactions in regional fire/vegetation models that seek to understand or predict historic and future responses of fire to climate and socioecological forcing (8, 53).

Methods

Fire activity in Sierra Nevada lower montane forests during the past four centuries was estimated by using tree-ring records of fire (1600–1907 CE) and 20th-century area burned data (1908–2015 CE). Wood samples with fire scars were collected from 29 sites on National Forest and National Park lands (Fig. 1 and Table S1). Logging and wildfires eliminated the fire scar record in many areas, precluding a systematic sampling scheme. Site elevation ranged from 1,136 to 2,437 m above sea level, and site collection areas ranged in size from 0.25 km^2 to 26 km^2. At each sample site, partial wood cross-sections with fire scars were removed from stumps, logs, or live trees with a chainsaw. An average of 67 (range, 10–440) partial wood cross-sections was extracted per site from primarily (90%) ponderosa pine trees. Fire dates in the wood samples were identified by cross-dating each sample's tree-ring series by using standard techniques (54). The calendar year of each ring with a fire scar in it was then recorded as the fire year.

An annual index of fire occurrence and extent (i.e., fire index) was calculated for each site by dividing the number of fire-scarred trees per year (with a minimum of two) by the number of trees potentially recording fire in that year (55). The start and end dates of these site fire index time series were determined by a minimum of four samples capable of recording fire. A Sierra Nevada-wide fire index was then calculated as sum of the site indices per year divided by the number of sites recording fire in that year (55). A cutoff date of 1600 CE was chosen for the fire regime-shift analysis to ensure a minimum sample of recording sites ($n = 9$, >25%; Fig. 2), a percentage sufficient to characterize fire regimes in frequent-fire forests (56).

Documentary records were used to develop the fire index for years after 1907. Area burned data for fires >40 ha in Sierra Nevada lower montane forests were selected from the interagency California digital database for the years 1908–2015. Data before 1908 were not used because they are less reliable (57). Index values were then calculated by dividing the area burned per year by the total area burned in all years (1908–2015 CE). Fire index values for the pre-1908 (i.e., fire-scar based) and post-1908 (i.e., area-based) periods were then merged to develop a continuous record.

Changes in the fire index time series that signify a regime shift were identified by using the method developed by Rodionov (58). Regime-shift detection is based on sequential *t* tests, and a regime-shift change is identified when the cumulative sum of normalized deviations from the mean value of a new regime is different from the mean of the current regime (58). A cutoff length of 30 y and a change point level of $P \leq 0.05$ were used to identify regime shifts, except for the individual analysis of the shorter 1900–2015 CE fire index time series, for which a cutoff length of 15 y and a change point level of $P \leq 0.1$ were used. The same procedures were used to identify regime shifts for proxies of (*i*) western North American summer temperature (WNAT) (59), (*ii*) summer moisture [Palmer Drought Severity Index (PDSI) for grid points 35 and 47) (60), (*iii*) winter Pacific-North American circulation pattern (61), (*iv*) winter Niño 3.4 index (62), and (*v*) annual Pacific Decadal Oscillation (63). To ensure that the regime shifts detected in the pre–20th-century fire index time series (1600–1907 CE) were not influenced by changes over time in the number of sites recording fire, we also conducted regime-shift analyses on fire index time series with a constant number of recording sites over time (Fig. S2). For this purpose, we developed fire index time series (as described earlier) based on only the nine sites (18, 24) that were recording fire since 1600 CE (1642 and 1686, respectively) and the 20th-century area-based fire index. These fire index time series were therefore based on a constant number of recording sites (9, 18, 24) during the pre-1908 section of their time series.

Correlation analysis, ANOVA, and graphical analysis were used to characterize fire–climate relationships in periods with different fire regimes and SESs (Table 1). We tested for differences in mean climate conditions among fire regimes and SESs by using ANOVA and a Tukey's post hoc test (64). Cross-correlation functions (CCF) and superposed epoch analyses (SEA) (65) were calculated to identify interannual fire–climate associations for the fire year and for lagged-years PDSI and WNAT (Figs. S3 and S4). Before calculating correlation coefficients, we removed serial autocorrelation by using autocorrelation functions and autoregressive moving average models (66). CCF and SEA were calculated for periods of different lengths identified by the regime-shift analysis and for the entire fire record.

To evaluate how interannual fire–climate relationships varied over time, we calculated 51-y running correlations between climate variables and fire index. Finally, to identify the influence of interdecadal climate variation on the fire index over time, we calculated the averages of the fire index and climate for 20-year nonoverlapping periods and calculated correlation coefficients (26, 64).

The relationship between 20-y averages of *z*-scores for the fire index and WNAT from 1600 to 1859 ($n = 13$) was assessed using a simple linear-regression model (64). This model was then used to predict the fire index for 1600–2015).

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