Global Ecology and Biogeography

WILEY

Global Ecology and Biogeography — A Journal of Macroecology

RESEARCH ARTICLE OPEN ACCESS

Spatiotemporal Synchrony of Climate and Fire Occurrence Across North American Forests (1750–1880)

Ellis Margolis[1] | Andreas Wion[1] | John Abatzoglou[2] | Lori Daniels[3] | Donald Falk[4] | Chris Guiterman[5] | James Johnston[6] | Kurt Kipfmueller[7] | Charles Lafon[8] | Rachel Loehman[9] | Maggie Lonergan[10] | Cameron Naficy[11] | Marc-André Parisien[12] | Sean Parks[13] | Jeanne Portier[14] | Michael Stambaugh[15] | Ellen Whitman[12] | A. Park Williams[16] | Larissa Yocom[17]

[1]New Mexico Landscapes Field Station, U.S. Geological Survey, Fort Collins Science Center, Fort Collins, Colorado, USA | [2]Management of Complex Systems, University of California Merced, Merced, California, USA | [3]Department of Forest and Conservation Sciences, University of British Columbia, Vancouver, British Columbia, Canada | [4]School of Natural Resources and the Environment and Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona, USA | [5]Cooperative Institute for Research in Environmental Sciences at the University of Colorado Boulder, and NOAA's NCEI, Boulder, Colorado, USA | [6]University of Oregon, Institute for Resilient Organizations, Communities, and Environments, College of Forestry, Eugene, Oregon, USA | [7]Department of Geography, Environment & Society, University of Minnesota, Minneapolis, Minnesota, USA | [8]Department of Geography, Texas A&M University, College Station, Texas, USA | [9]USGS Alaska Science Center, Anchorage, Alaska, USA | [10]Cooperative Institute for Research in Environmental Sciences at the University of Colorado Boulder, Boulder, Colorado, USA | [11]Ecology Program and Forest Health Protection, Pacific Northwest Region, USDA Forest Service, Portland, Oregon, USA | [12]Canadian Forest Service, Natural Resources Canada, Edmonton, Alberta, Canada | [13]Aldo Leopold Wilderness Research Institute, Rocky Mountain Research Station, USDA Forest Service, Missoula, Montana, USA | [14]Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Switzerland | [15]University of Missouri, Columbia, Missouri, USA | [16]Department of Geography, University of California Los Angeles, Los Angeles, California, USA | [17]Wildland Resources Department, Utah State University, Utah, USA

Correspondence: Ellis Margolis (emargolis@usgs.gov)

Received: 19 March 2024 | **Revised:** 4 September 2024 | **Accepted:** 4 November 2024

Handling Editor: Daniel McGlinn

Funding: This work was supported by the USGS John Wesley Powell Center for Analysis and Synthesis, the USGS Ecosystems Land Change Science Program, the USGS Southwest Climate Adaptation Science Center, the Gordon and Betty Moore Foundation, and the Sustainable LA Grand Challenges program at UCLA.

Keywords: climate | fire | fire scar | regionalisation | synchrony | tree ring

ABSTRACT

Aim: Increasing aridity has driven widespread synchronous fire occurrence in recent decades across North America. The lack of historical (pre-1880) fire records limits our ability to understand long-term continental fire-climate dynamics. The goal of this study is to use tree-ring reconstructions to determine the relationships between spatiotemporal patterns in historical climate and widespread fire occurrence in North American forests, and whether they are stable through time. This information will address a major knowledge gap required to inform projections of future fire.

Location: North American Forests.

Time Period: 1750–1880 CE.

Major Taxa Studied: Trees.

Methods: We applied regionalisation methods to tree-ring reconstructions of historical summer soil moisture and annual fire occurrence to independently identify broad- and fine-scale climate and fire regions based on common inter-annual variability.

Ellis Margolis and Andreas Wion contributed equally to this work.

We then tested whether the regions were stable through time and for spatial correspondence between the climate and fire regions. Last, we used correlation analysis to quantify the strength of the fire-climate associations through time.

Results: We found that broad-scale historical patterns in climate and fire have strong spatial coherence. Although climate and fire regions vary over time, large core areas of the regions were stable. The association between climate and fire varied through time and was strongest in western North America, likely due to a combination of factors, such as the magnitude of drought frequency and severity, as well as varying use of fire by human communities.

Main Conclusions: The historical perspective gained through tree-ring reconstructions of climate and fire patterns and their association suggests that climate-driven synchrony of fire across large areas of the continent in recent decades is not unprecedented, will likely continue into the future, and may exhibit similar spatial patterns.

1 | Introduction

Climate change is a primary driver of increasing annual area burned and widespread synchronous fire over large areas of North America in recent decades (Abatzoglou and Williams 2016; Parisien et al. 2023; Turco et al. 2023). Large fires burned > 40,000 km^2 in the United States during 2015, 2017 and 2020 (NIFC 2024), and 150,000 km^2 in Canada during the exceptional 2023 fire season. Widespread fire overwhelms firefighting resources (Abatzoglou et al. 2021), degrades air quality and increases health risks near and far from the fires (Reid et al. 2016; Burke et al. 2021), increases hazardous weather downwind of fires (Zhang et al. 2022) and creates positive feedbacks that accelerate the release of greenhouse gasses into the atmosphere (Walker et al. 2019; Zhao et al. 2021). In many locations, increasing fire frequency and severity is catalysing type conversion of forests to non-forest vegetation (Coop et al. 2020). The increasing effect of climate-driven, widespread synchronous fire on societies and ecosystems highlights the need to understand fire-climate relationships.

To characterise fire-climate relationships at the continental scale, it is important to identify regions with synchronous patterns of climate and fire. Schroeder and Buck (1970) first proposed North American fire-climate regions based on similar fire-weather characteristics as a framework for understanding climate drivers of broad-scale fire patterns. Recent data-driven attempts to classify fire into 'pyromes' or 'fire zones' are similar to the classic climate classifications (e.g., Köppen 2011), in that they group similar components of a fire regime (e.g., frequency, intensity, season and fire size; Archibald et al. 2013; Boulanger, Gauthier, and Burton 2014; Erni et al. 2019; Cattau et al. 2022). In contrast, less attention has been given to identifying fire regions based on broad-scale synchrony, despite the increasing effects of widespread synchronous fire. We define synchrony as the occurrence of climatic anomalies or multiple wildfires in the same year such that an entire region could be affected by drought or extensive burning. Regions of broadly synchronous climate have been defined using regionalisation methods for subregions of the North American monsoon (Comrie and Glenn 1998) and historical drought footprints in the continental United States (Meko et al. 1993; Fye, Stahle, and Cook 2003). Applying similar methods to define regions with common interannual variability of historical fire occurrence would advance our understanding of continental fire patterns and could be used to test for climate drivers of widespread synchronous fire.

Top-down and bottom-up factors influence synchronous fire, but the spatiotemporal variability of their relative importance is uncertain at the continental scale. Climate acts as a top-down driver of fire activity, synchronising fuel aridity and fire weather across large spatial extents (Swetnam and Betancourt 1998; Abatzoglou and Williams 2016; Cardil et al. 2023). Bottom-up factors like fuel continuity, topography, ignitions and Indigenous fire management are important influences on fire synchrony at local scales (Gill and Taylor 2009; Parks, Parisien, and Miller 2012; Swetnam et al. 2016; Foster et al. 2022; Stambaugh et al. 2018). Identifying spatiotemporal patterns of contemporary fire occurrence to disentangle the relative influences of top-down and bottom-up factors is limited to the last few decades, a relatively short period over which we have continental-scale satellite-based fire records (e.g., Monitoring Trends in Burn Severity; Eidenshink et al. 2007). The analysis of tree-ring records of climate and fire prior to 1900 has greatly expanded our understanding of the varying influences of climate on fire patterns (Swetnam and Betancourt 1990; Kitzberger et al. 2007; Heyerdahl et al. 2008; Yocom et al. 2010; Johnson and Kipfmueller 2016; Taylor et al. 2016; Lafon et al. 2017; Marschall et al. 2019; Chavardès et al. 2021), but these studies have largely been limited to local or regional scales. Recent advances in continental-scale climate reconstructions (Cook, Woodhouse, and Eakin 2004; Williams et al. 2020) and palaeofire records, such as the North American Fire Scar Network (NAFSN, Margolis et al. 2022), provide opportunities to define and test for spatial and temporal relationships between patterns of synchrony of climate and fire across North America prior to the twentieth-century fire suppression era.

The goal of this study is to determine the relationships between spatiotemporal patterns in historical climate and widespread fire occurrence in North American forests, and whether they are stable through time. This will provide insights into the spatiotemporal variability of fire and the relative importance of top-down and bottom-up influences on widespread, synchronous fire occurrence. By combining continental tree-ring reconstructions of climate and fire occurrences from 1750 to 1880 with regionalisation methods, we address the following objectives: (1) quantify the geographical extent of historical synchrony of North American climate and fire; (2) identify geographic regions of synchronous climate and fire; (3) test for stability in climate and fire regions over time; and (4) test for temporal variability in fire-climate relationships among the regions.

2 | Methods

2.1 | Study Area

Our study area includes North America between 20°N and 60°N (Figure 1). We used this latitudinal range because outside of this area there are few tree-ring fire history sites with sufficient data prior to 1880 CE (Margolis et al. 2022). The fire data reconstructed from tree rings are located in forested regions, consequently, our results apply to forest fire regimes.

2.2 | Fire Data and Processing

We analysed records of fire occurrence for the period 1750–1880 from NAFSN (Margolis et al. 2022), using tree-level records of the year of fire occurrence from 1159 sites. The start year of the analysis, 1750, was chosen to optimise the longest possible period with the broadest geographic coverage of sites that were continuously recording fire. Continuously recorded fire data are necessary to prevent biases in the cluster analysis related to decreasing sample depth associated with tree-ring sample decay (Swetnam, Allen, and Betancourt 1999). The analysis period ended in the year 1880 due to the strong influence of fire exclusion from unregulated grazing and timber harvest, disrupted Indigenous burning and fire suppression (Swetnam et al. 2016), although the timing, cause and level of fire exclusion vary across the study area (Margolis et al. 2022).

We used the *burnr* package in R (v0.6.1, Malevich, Guiterman, and Margolis 2018) and applied two filters to the site-level fire-scar data to include fire occurrences that were: (1) replicated within each site (≥ 2 trees scarred per site) and (2) recorded by 10% or more of trees within each site. The minimum-tree filter has a larger influence on small sites with few trees, while the per cent-scarred filter reduces the influence of large sites (e.g., >20 trees; Falk et al. 2007). This combination of filters is commonly used in fire history analyses (e.g., Swetnam and Baisan 1996) to minimise the effects of varying sample depth among sites and reduce the contribution of small fires that may obscure the signal of widespread synchronous fires. To normalise for the higher density of NAFSN sites in the West, we aggregated fire data from the sites into hexels with a diameter of 100 km (hexel area 8660 km^2; Figure 1) and produced a time series of per cent of sites scarred in each hexel per year.

2.3 | Climate Data

To represent historical climate (1750–1880), we used tree-ring reconstructed soil moisture as a proxy for fuel aridity (e.g.,

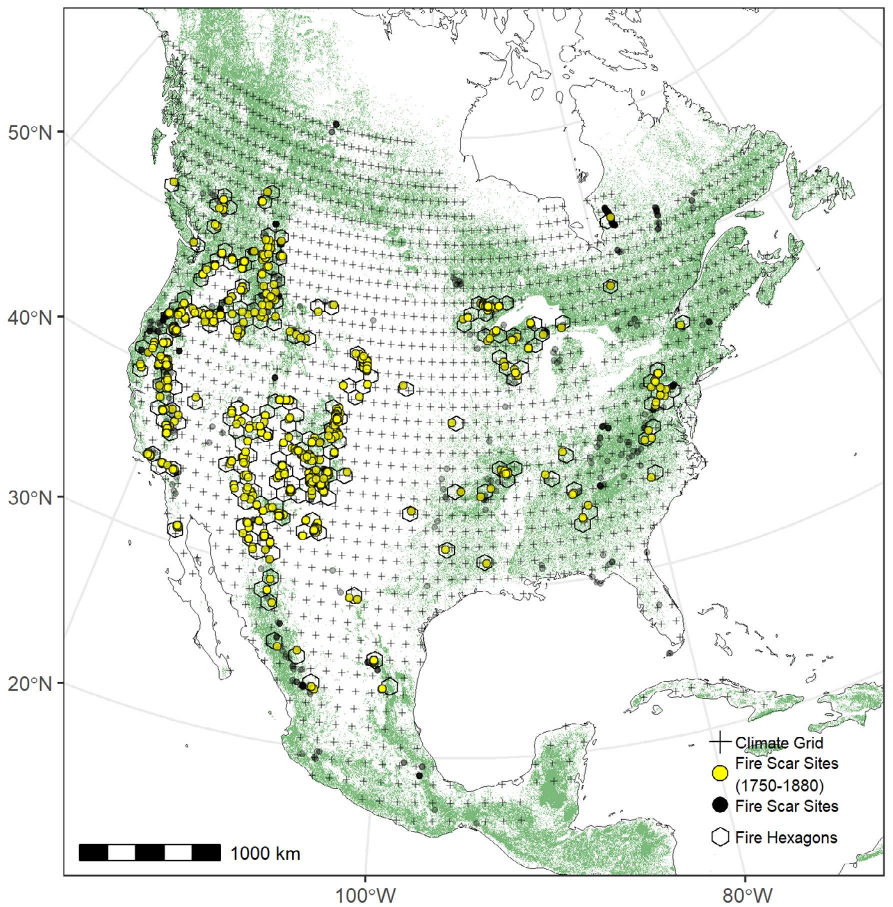

FIGURE 1 | Map of the North American Fire Scar Network sites (dots) and summer (June–August) soil moisture grid (black crosses) reconstructed from tree rings across the study area. Fire-scar sites that met our inclusion criteria (continuously recording replicated fires from 1750 to 1880; see methods for details) are yellow, whereas sites that did not meet these criteria are black. Site-level fire data were aggregated within hexagons for analysis. Green shading is forest cover from Hansen et al. (2022) downloaded via Google Earth Engine.

Williams, Cook, and Smerdon 2022). An existing continental reconstruction of summer soil moisture (June–August; JJA, Williams et al. 2020) was extended to cover the spatial extent of the tree-ring fire-scar sites (Figure 1). The established reconstruction method relates climate-sensitive tree-ring widths to modern gridded soil moisture products using point-by-point regression, producing annual grids for all forested regions of North America (north of 14° latitude) at 1° × 1° resolution. Anomalies were calculated as standardised (z-scored) values relative to the 1901–2000 mean at each point. The skill of the model reconstruction varied over time and across space but was highly robust (with R^2 values > 0.5) for much of the continent between 1750 and 1880 (Figure S1). Because there are more tree-ring chronologies in the western versus the eastern regions, reconstruction skill is strongest there; however, we were interested in exploring patterns of climate synchrony more broadly and so include areas where the absolute reconstructed values may have lower accuracy, but where we believe the general pattern of variability (and thus synchrony) is adequate for our comparisons to fire. To not over-extend the spatial scale of our analysis, we omitted grid points beyond 20°–60° north latitude to account for the distribution of fire-scar sites and the noted decrease in model skill evident in boreal regions (Figure S1).

2.4 | Quantifying the Scale and Extent of Synchrony in Historical Climate and Fire

To quantify the strength and spatial extent of synchrony for climate and fire, we calculated spatial autocorrelation using spline correlograms. Correlograms show the change in pairwise correlations between observations at increasing distances. We used the annual percentage of sites scarred per hexel to calculate fire correlograms; for climate we extracted the annual mean value of summer soil moisture underlying each fire hexel. This resulted in an equally sized and identically spaced grid of climate and fire points for spatial autocorrelation comparisons. We ran bootstrap simulations with 100 replicates to determine the confidence interval of the spline correlograms, then plotted these curves against each other to compare the spatial synchrony by distance relationship for climate and fire, independently. We also calculated the cross-correlogram, which quantifies change in the pairwise correlations between the climate and fire series at increasing distances.

2.5 | Identifying Regions and Subregions of Synchronous Climate and Fire and Their Stability Through Time

We used regionalisation to independently identify spatially contiguous regions with common variability in historical summer soil moisture and fire occurrence. Regionalisation is a statistical method that identifies spatially contiguous groups that are more correlated within than between regions (White, Richman, and Yarnal 1991; Yarnal 1993). In ecology, similar methods are used with multivariate data without a temporal component (e.g., species composition, traits, characteristics of fire regimes). Here, we performed regionalisation on the annual time series of historical gridded climate and hexel-level fire occurrence to identify shared spatial patterns among widespread synchronous climate anomalies and fire years.

We evaluated multiple regionalisation procedures using the *HiClimR* package in R (Badr, Zaitchik, and Dezfuli 2015). *HiClimR* applies hierarchical clustering to a weighted composite distance matrix. Two observations that are adjacent are weighted to be more similar than two observations that are far apart, imposing a geographic 'contiguity' constraint on the data to help identify spatially contiguous regions. We set the constraint to 1 in *HiClimR*, which equates to a 2.2% weight of geography versus a 97.8% weight on the synchrony of climate or fire. Distance was calculated between the centroids of climate grid points or fire hexels. Dissimilarity was calculated as Euclidean distances of per cent of sites scarred by fire among hexels or between standardised climate anomalies among pixels. We used Ward's method as our choice of the linkage method, which groups observations by minimising within-cluster variance (Murtagh and Legendre 2014). Climate and fire regions were identified independently.

To determine the number of regions, we adopted a data-driven approach to limit subjectivity. To identify the optimal clustering solutions (i.e., number of regions), we iterated cluster analyses across different numbers of regions ($k = 2$ to 10) and evaluated the strength of the solution for each k. Cluster strength and the final number of regions were chosen by evaluating a combination of the mean 'intraCluster' correlation, a measure of similarity *within* regions, and the maximum 'interCluster' correlation, a measure of pairwise similarity *between* two regions (Badr, Zaitchik, and Dezfuli 2015). We chose two final cluster solutions for climate and fire, independently, representing different spatial scales; broad-scale 'regions' and fine-scale 'subregions'. The two solutions were determined from the primary and secondary optima of our validation statistics. The broad-scale regional solution identifies fewer, large regions (lower k) and was chosen to maximise the within-group correlations, while minimising between-group correlations. The fine-scale subregional set of solutions identifies a greater number of smaller subregions (higher k), by maximising within-region correlation (homogeneity) at the expense of a more relaxed threshold for between-region correlations (maximum between-region correlation < 0.5).

To examine the stability of the regions and subregions through time, we split the data in half at the midpoint of the analysis period and re-analysed cluster strength for regions and subregions. The two time periods are 1750–1815 (T1) and 1816–1880 (T2). To assess spatial coherence between climate and fire regions, we calculated goodness of fit (GOF) statistics using the *mapcurves* algorithm (Hargrove, Hoffman, and Hessburg 2006) implemented in the *sabre* package in R (Nowosad and Stepinski 2018). *Mapcurves* calculates the per cent agreement of multiple class-based categories from two sets of maps, with values ranging from 0 (perfect disagreement) to 1 (perfect agreement). Specifically, we calculated the GOF between climate and fire regions and subregions, for each time period, T1 and T2. We then calculated the GOF between time periods, T1—T2, for regions and subregions, as a measurement of stability through time.

2.6 | Quantifying Spatiotemporal Variability in Fire-Climate Relationships

We quantified the relationships between the climate and fire regions and subregions by calculating Pearson correlation coefficients. For the broad-scale regions, we identified the fire region with the greatest overlap with each climate region. We then extracted an annual time series of mean soil moisture for each climate region and compared these against the mean annual per cent of sites burned among all hexels in the corresponding fire region. For each climate-fire region pair, we calculated 50-year moving window correlations across the length of the time series to understand how this relationship changes over time. For the fine-scale subregions, we took the mean of the climate pixels underlying each fire subregion and correlated them against the subregional time series of fire. All analyses were conducted in R (V. 4.2.0; R Core Team 2022).

3 | Results

3.1 | Scale and Extent of Climate and Fire Synchrony

Climate and fire exhibited varying spatial autocorrelation at different distances, with climate showing stronger spatial autocorrelation than fire (Figure 2A). Fire was weakly synchronous at scales less than 600 km, whereas climate was strongly to moderately synchronous at scales up to 1000 km. The cross-correlation between climate and fire suggests a weak fire-climate relationship at distances < 1000 km (i.e., low soil moisture associated with high fire), which then flips to a weaker inverse relationship at greater distances (Figure 2B).

3.2 | Broad-Scale Regional Patterns

The broad-scale regional clustering solution independently identified three regions (i.e., $k = 3$) within North America for both summer soil moisture and fire from 1750 to 1880 that had similar

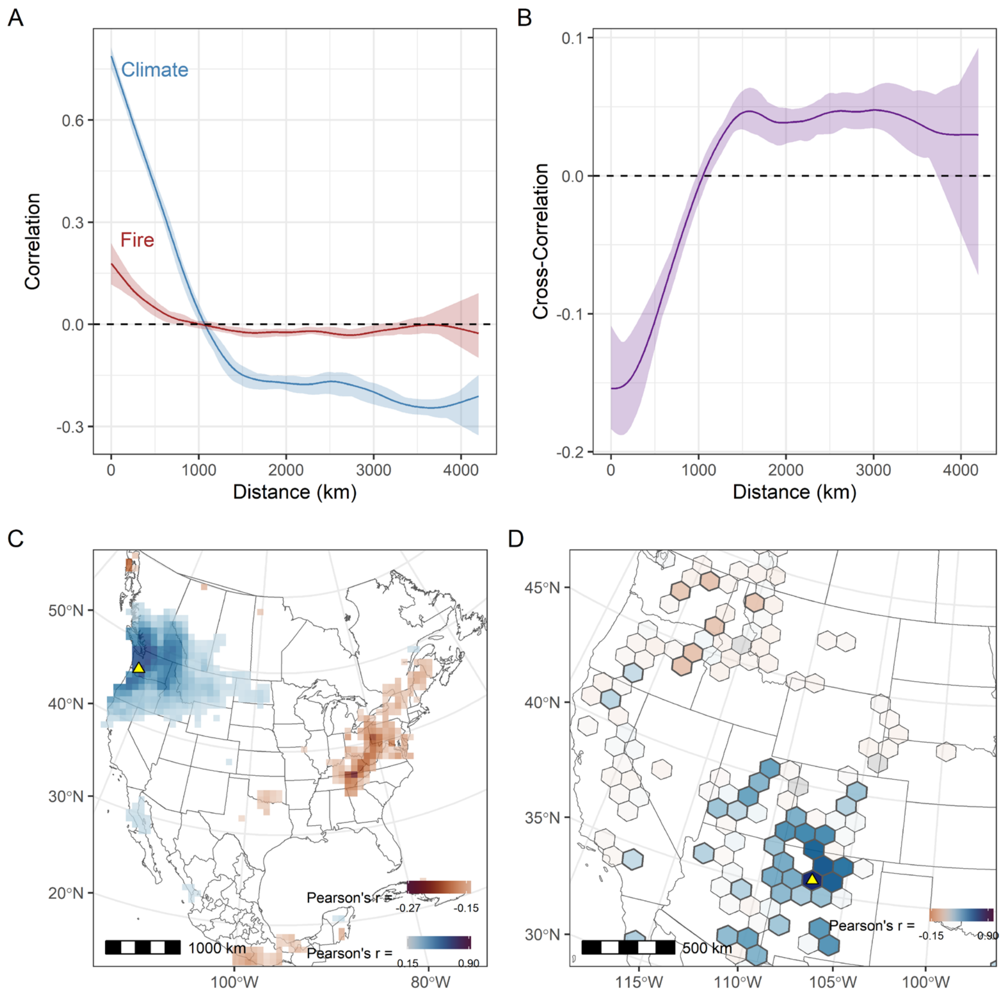

FIGURE 2 | (A) Spatial autocorrelation of historical summer (June–August) soil moisture anomalies and the per cent of tree-ring sites burned within a hexel (1750–1880). (B) Cross-correlation correlogram between historical summer soil moisture anomalies and the per cent of tree-ring sites burned, showing the strength and sign of the relationship between climate and fire at varying distances. The shading around the lines represents the 95% confidence intervals determined from 100 bootstrap simulations. (C) Example of the spatial synchrony of summer soil moisture, illustrated by pairwise correlations for a single pixel located in Washington (yellow triangle) and all other pixels. (D) Example of the spatial synchrony of fire from western North America, illustrated by pairwise correlations between the per cent of sites burned in a single hexel in northern New Mexico (yellow triangle) and all other fire hexels.

spatial patterns (Figures 3 and S2). The cluster solutions were spatially and statistically robust, but climate and fire differed in the strength of their clustering. Climate regions had higher within-region synchrony than fire, evidenced by higher within-region correlations (within-region correlation range = 0.32 to 0.45 for climate, 0.18 to 0.30 for fire; all statistically significant at $p < 0.05$). The climate and fire regions organised into three coarse-scale regions in the Northwest, Southwest and East that had broad spatial correspondence (mapcurves GOF = 0.64, Figure 3A).

There were significant correlations between the time series of summer soil moisture and fire in the Northwest ($r = -0.34$, $p < 0.001$) and the Southwest ($r = -0.43$, $p < 0.001$), but not in the East ($r = -0.11$, $p = 0.23$; 1750–1880, Figure 3B). Fire-climate relationships in each region varied through time, with a general trend of decreasing strength towards the present in all regions (Figure 3C). The Northwest deviated slightly from this general trend, in that correlation began strengthening around 1830 after the weakening trend from 1750 to 1830 (Figure 3C). The Southwest had the strongest 50-year running correlations ($r = -0.63$) that were significant over the full period, whereas correlations in the Northwest were weaker than $r = -0.28$ ($p > 0.05$) during 50-year periods centred on 1800–1840. In the East, 50-year correlations ranged from −0.29 (50-year period centred on 1803) to 0.11.

When the analyses were split into two time periods, the optimal clustering solution resulted in three broad-scale regions for both summer soil moisture and fire in T1 (1750–1815) and T2 (1816–1880; Figure 4), which is broadly similar to that of the full period (Figure 3). Within-group correlations for climate regions ranged from $r = 0.32$ to 0.43 ($p < 0.05$) for T1 and $r = 0.35$ to 0.48 for T2 ($p < 0.05$). Within-group correlations for fire regions ranged from $r = 0.21$ to 0.28 for T1 and $r = 0.17$ to 0.29 for T2. For the Northwest and Southwest regions, within-group correlations

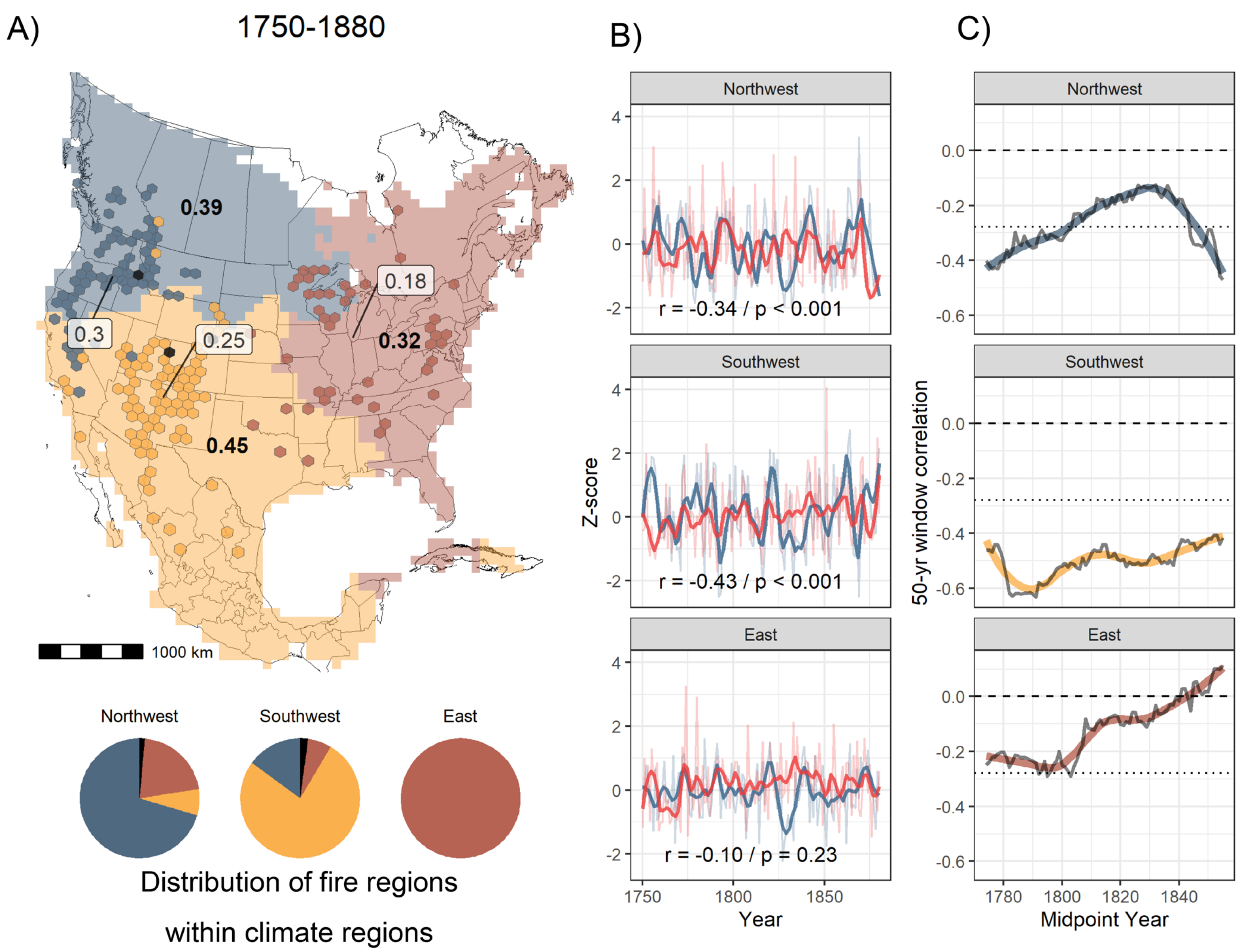

FIGURE 3 | (A) Regions of historical summer soil moisture (underlying grid) and fire (hexels) in North America (1750–1880). Climate and fire regions displayed are the Northwest (blue), Southwest (yellow) and East (red). Black hexels did not cluster with a group. Within-region correlations are indicated by bold numbers for climate and boxed numbers for fire. Pie charts illustrate the spatial similarity between the climate and fire regions calculated as the per cent of fire hexels that fall within the corresponding climate region (e.g., 100% of the fire hexels within the East climate region are from the East fire region). (B) Cluster mean (z-score) time series of annual per cent of sites burned (red) and summer soil moisture (blue) for each fire region and their correlations (r). The soil moisture time series are inverted for better visual comparison with the fire time series. The dark lines are locally estimated scatterplot smoothing (LOESS) trends of the annual means using a 10% sliding window. (C) Running 50-year correlations between soil moisture and the annual per cent of sites scarred for each fire region. The dark-coloured lines are LOESS trends of the 50-year running correlation using a 50% sliding window. Correlations below the horizontal dotted line at $r = -0.28$ are significant ($p < 0.05$).

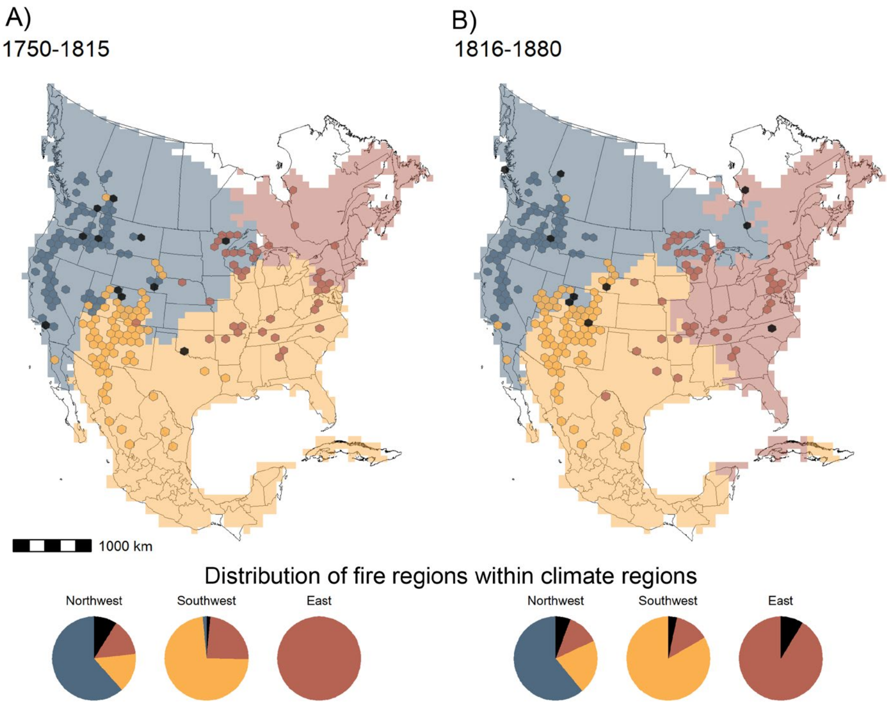

FIGURE 4 | Regions of summer soil moisture (underlying grid) and fire (hexels) from 1750 to 1815 (T1; A) and 1816 to 1880 (T2; B). Climate and fire regions displayed are the Northwest (blue), Southwest (yellow) and East (red). Black hexels did not cluster with a group. Pie charts illustrate the spatial similarity between the climate and fire regions for each time period calculated as the per cent of fire hexels in each fire region that fall within the corresponding climate region (symbology as in Figure 3).

were statistically significant for both time periods, but not in the East in T1 or T2.

The spatial pattern of the three climate and fire regions was relatively stable between T1 and T2 in the West, but shifted noticeably in the East, particularly for the climate regions. Relative to T1, the East climate region expands south in T2, extending from eastern Canada and the northeastern US down to the southeastern United States (Figure 4). The spatial patterns of the fire regions were generally stable through time, although the East fire region expanded slightly in T2. Mapcurves GOF scores describing the spatial relationship between the climate and fire regions were 0.57 for T1 and 0.63 for T2, similar to the full period. Testing for stability of the spatial patterns of the fire regions between T1 and T2 indicated high agreement (GOF = 0.88), but less stability through time for the climate regions (T1 vs. T2 GOF = 0.67).

3.3 | Fine-Scale Subregional Patterns

The fine-scale subregional clustering solution independently identified nine climate and fire subregions over the full-time period (Figure 5). Subregions exhibited higher within-group correlations than the three broad-scale regions, ranging from 0.35 to 0.76 for summer soil moisture and 0.26–0.61 for fire. These correlations were statistically significant for all regions ($p < 0.05$). The fire subregions had moderate spatial overlap with the climate subregions (mapcurves GOF = 0.54). Climate and fire subregions had higher between-group correlations than the regions (Table S1), but all were below our separability criterion of 0.5 (Figure S2).

The nine climate and fire subregions identified for the full-time period reduced to eight climate and eight fire subregions during T1 (Figure 6). The subregions reorganised to six climate and seven fire subregions during T2. There was relatively poor spatial correspondence between climate and fire subregions during T1 (GOF = 0.36) and T2 (GOF = 0.45). Fire subregions were moderately stable through time (T1–T2 GOF = 0.56). Climate subregions were slightly more stable through time, with a GOF score of 0.62.

Fire-climate relationships varied significantly among subregions and through time. Correlations between summer soil moisture and per cent of sites burned were generally stronger in the West than in the East (Figure 7), with 50-year correlations ranging from −0.77 in the Pacific Northwest (centred on the year 1776) to 0.07 in Appalachia (centred on 1788). All subregions except Appalachia had at least one 50-year time period with a significant correlation ($r \leq -0.28$). There was no detectable common trend in the variability of fire-climate relationships through time among subregions; some decreased in strength over time (e.g., Colorado Plateau), others increased (e.g., Black Hills) and multiple records had noticeable changes centred on the early 1800s (e.g., Sierra Nevada, Northern Forests, Mississippi Valley and Southern Rockies).

4 | Discussion

4.1 | Climate Drives Widespread Fire Synchrony

We found that summer soil moisture—an indicator of fuel aridity—was historically synchronous across large regions of North America and that these climate regions likely influenced spatial

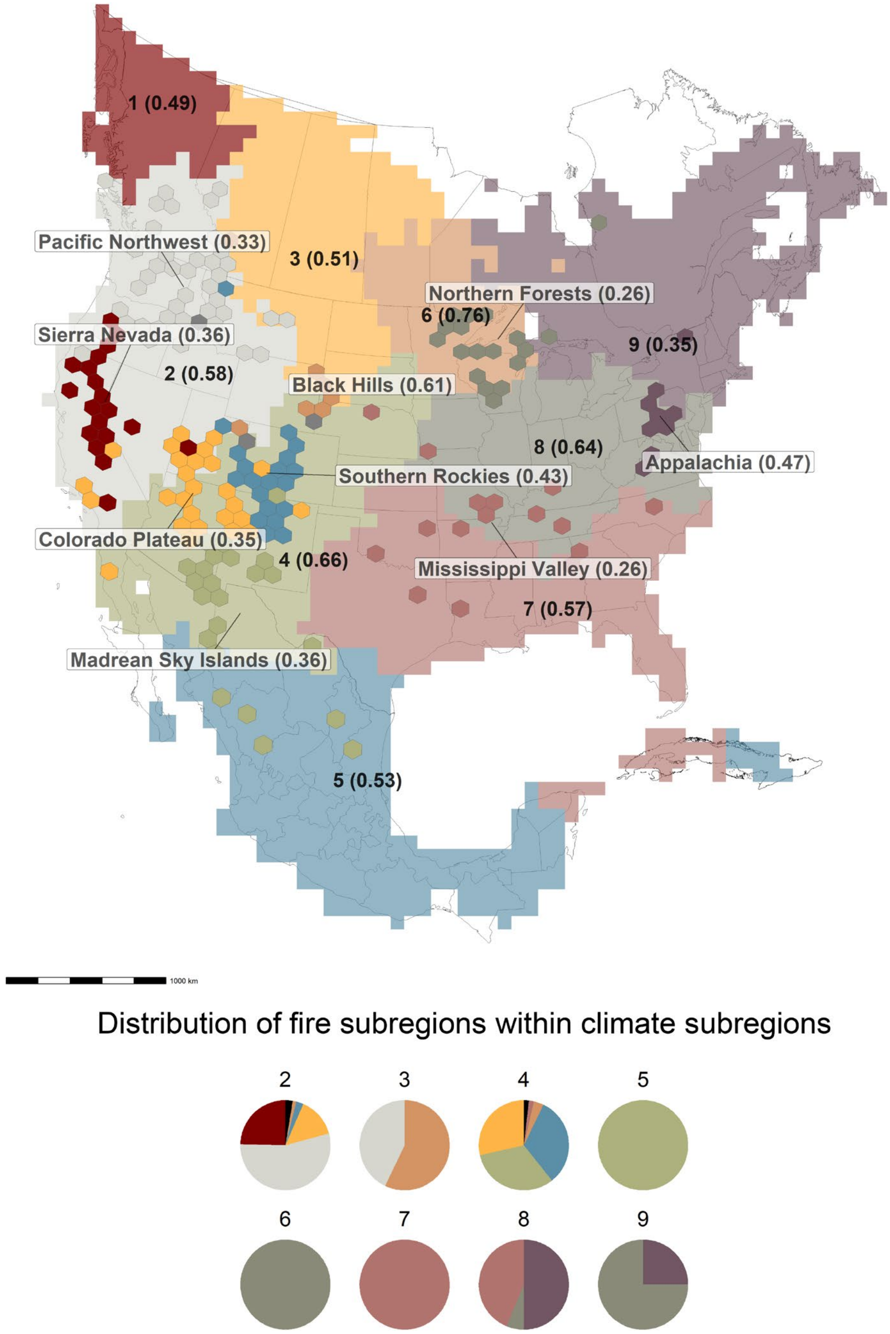

FIGURE 5 | Historical summer soil moisture (underlying grid) and fire (hexel) subregions in North America (1750–1880). Climate subregions are numbered and fire subregions are named. Values indicate within-group similarity of subregions (fire = boxes, climate = bold text) calculated as the average correlation of all cells in a subregion with the cluster mean. Pie charts illustrate the spatial similarity between the climate and fire subregions calculated as the per cent of fire hexels in each fire region that fall within the corresponding climate region (symbology as in Figure 3).

patterns of widespread fire occurrence. Drought influences on fuel aridity are an increasingly important top-down driver of widespread synchronous fires in recent decades (Abatzoglou and Williams 2016; Coop et al. 2020). Climate is known to have broad influences on a wide array of ecological processes (Walter et al. 2017), such as tree seed production, seedling survival and establishment, bird migration and animal population dynamics (Post and Forchhammer 2002; Cheal et al. 2007; Koenig and Liebhold 2016; LaMontagne et al. 2020; Littlefield et al. 2020). Although patterns and relationships between climate and fire synchrony in North America have been previously studied at the regional level (Brown and Wu 2005; Morgan, Heyerdahl, and Gibson 2008; Trouet et al. 2010; Abatzoglou and Kolden 2013; Yocom Kent et al. 2017), until the compilation of the NAFSN it was not possible to evaluate broad-scale relationships across the continent in prior centuries. Synchrony is an emergent property of both climate and fire, and our results improve the understanding of the spatial scale of synchrony in historical climate and fire patterns, as well as their relationships.

The relative spatial stability of large climate and fire regions suggests that climate was a consistent influence on widespread

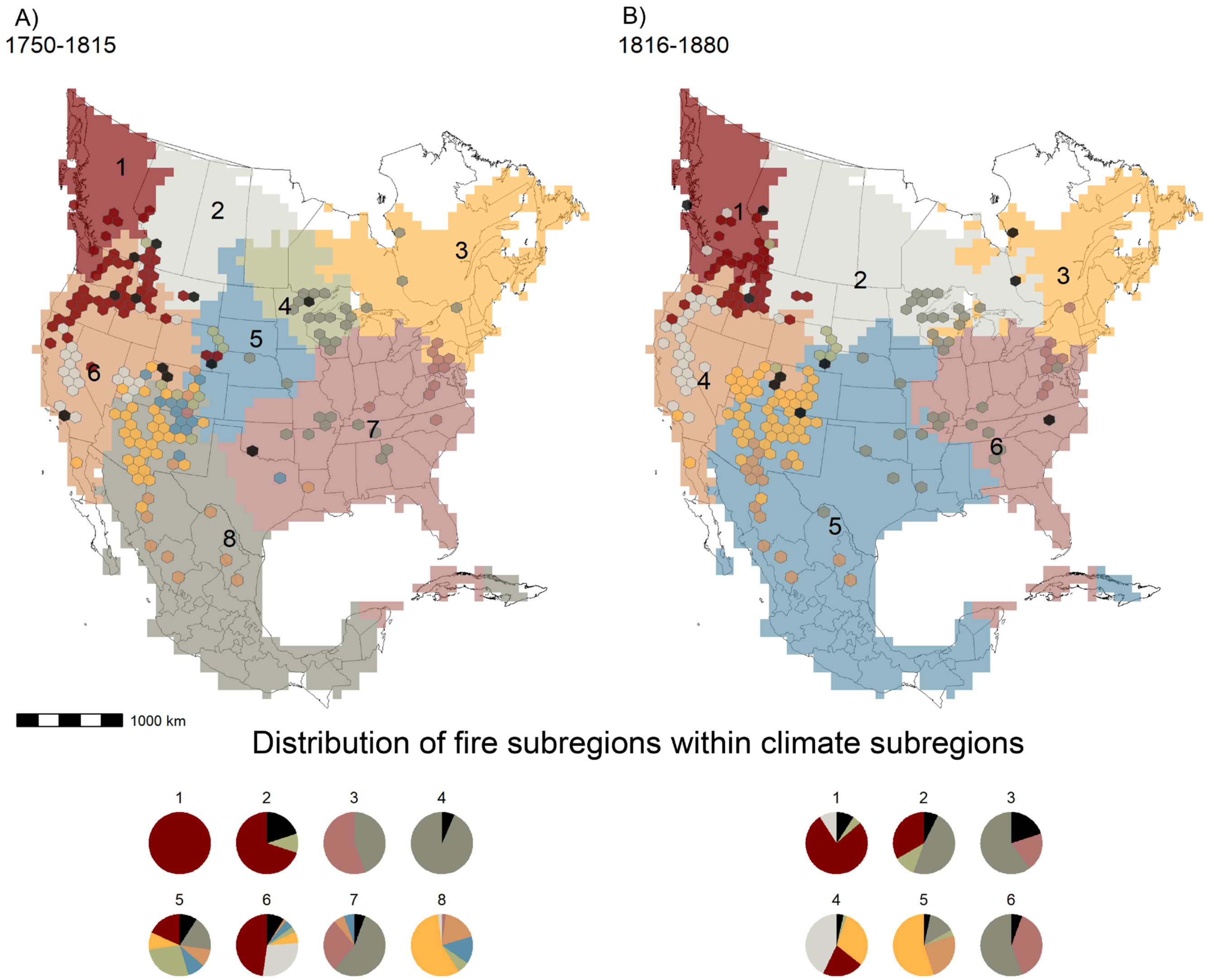

FIGURE 6 | Subregions of summer soil moisture (underlying grid) and fire (hexels) from 1750 to 1815 (T1; A) and 1816 to 1880 (T2; B). Climate regions are numbered. Pie charts illustrate the spatial similarity between the climate and fire subregions for each time period calculated as the per cent of fire history hexels by fire region that fall within the corresponding climate region (symbology as in Figure 3).

synchronous fire occurrence. Inter-annual variability of ocean–atmosphere teleconnections such as ENSO produce well-documented and predictable patterns of synchronous drought in North America in the palaeo and modern periods (Kiladis and Diaz 1989; Gershunov and Barnett 1998; Woodhouse et al. 2010), which are modulated by multi-decadal variability of Pacific and Atlantic teleconnections (McCabe, Palecki, and Betancourt 2004). Drought associated with these teleconnections has been linked to historical and modern patterns of widespread synchronous fire (Swetnam and Betancourt 1998; Kitzberger et al. 2007; Macias Fauria and Johnson 2008; Meyn et al. 2010; Yocom et al. 2010; Cardil et al. 2023). Other continental-scale climate phenomena that influence synchronous patterns of drought and fire include the latitudinal position and strength of the jet stream (Dannenberg and Wise 2017; Wahl et al. 2019; Jain and Flannigan 2021), and the strength of the North American monsoon (Arizpe et al. 2020; Bai, Strong, and Zuckerberg 2023). As anthropogenic climate change amplifies drought to a scale and severity not seen in the last millennium (Cook, Ault, and Smerdon 2015), understanding the persistence and influences of the phenomena that modulated past patterns of widespread synchronous drought (e.g., Pascale et al. 2017; Mann et al. 2018; Wahl et al. 2019; Osman et al. 2021) is important to understand climate-driven patterns of future fire.

Fire synchrony was weaker and less spatially coherent than climate synchrony, likely due to highly variable bottom-up influences on fire within and among regions. Topography, spatial and temporal variability of fuels, and ignitions are strong bottom-up influences on fire (Gill and Taylor 2009; Parks, Parisien, and Miller 2012). In addition, humans have influenced fire regimes for centuries to millennia through Indigenous burning, fuelwood use, vegetation manipulation and land clearing, livestock grazing and active fire suppression (Swetnam et al. 2016; Taylor et al. 2016; Balch et al. 2017; Stambaugh et al. 2018; Kipfmueller et al. 2021; Roos et al. 2022; Copes-Gerbitz, Daniels, and Hagerman 2023; Johnston et al. 2023; Tulowiecki, Hanberry, and Abrams 2023). These local factors were likely more influential on fire synchrony at the finer-scale subregions

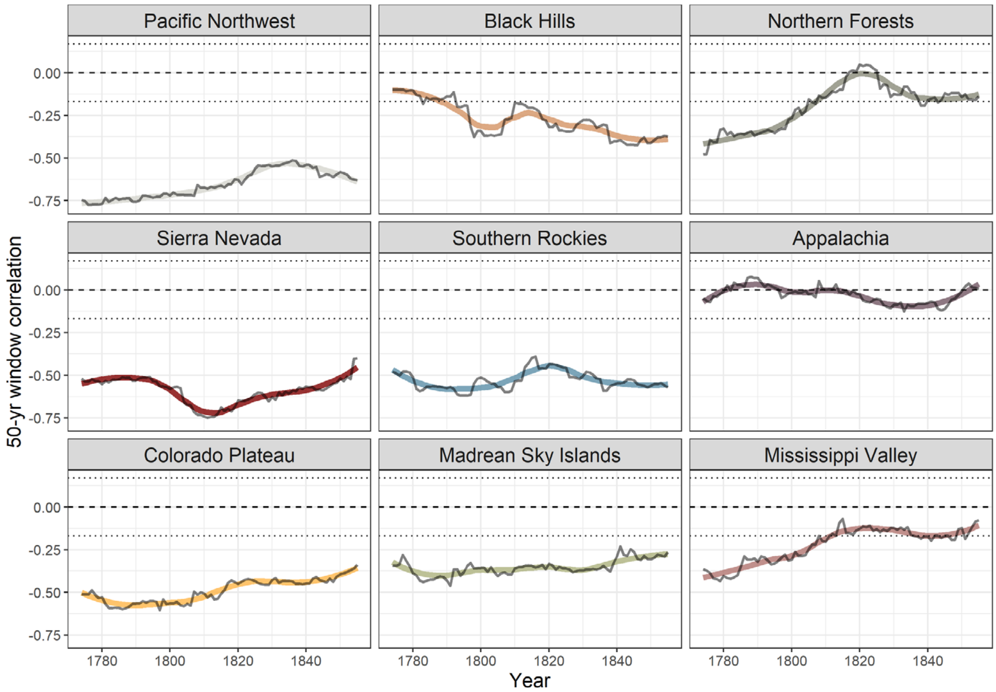

FIGURE 7 | Running 50-year correlations between summer soil moisture and the annual per cent of sites burned for each fire subregion in North America (1750–1880). Refer to Figure 5 for subregion locations. The dark-coloured lines are locally estimated scatterplot smoothing (LOESS) estimated trends for the 50-year running correlations using a 50% moving window. The dotted horizontal line indicates the threshold for a significant negative correlation ($r \leq -0.28$, $p < 0.05$).

than the broad-scale regions we identified, as evidenced by the greater discrepancies between spatial patterns of climate and fire synchrony of the subregions (Figure 5) than at the regional scale (Figure 3A). The timing of human effects on these different bottom-up factors varied throughout the continent and undoubtedly influenced the strength of the fire-climate associations through time (see Section 4.2).

4.2 | Spatiotemporal Variability of Fire-Climate Relationships

Relationships between climate and fire varied spatially among regions of North American forests. Correlations between climate and fire were generally stronger in western regions than in the east, consistent with prior research (Guyette, Muzika, and Dey 2002; Kitzberger et al. 2007; Yocom et al. 2010; Lafon et al. 2017; Stambaugh et al. 2018; Sutheimer et al. 2023). The weaker fire-climate relationships in eastern North America do not imply that climate is unimportant; climate forcing has been linked to historical fire occurrence in the Great Lakes (Kipfmueller et al. 2017; Sutheimer et al. 2023), the eastern United States (Aldrich et al. 2014; Marschall et al. 2019; Howard et al. 2021) and Canada (Girardin et al. 2006; Harvey and Smith 2017). Rather, multiple non-climatic factors—Indigenous burning, a high number of human ignitions relative to lightning ignitions, legacies of land ownership, the timing of colonisation and drought duration and severity—can dampen the influence of climate on fire (Fulé et al. 2012; Meunier, Romme, and Brown 2014; Taylor et al. 2016; Balch et al. 2017; Hoffman, Lertzman, and Starzomski 2017; Campos-Ruiz, Parisien, and Flannigan 2018; Roos et al. 2022).

Relationships between climate and fire varied through time across North American forests. We found a trend of decreasing strength of fire-climate relationships at the regional scale between 1750 and 1880, but also found varying, and sometimes contrasting trends among different subregions. The different patterns at the different spatial scales likely indicate varying relative influences of top-down (climate) and bottom-up (human) influences on fire-climate relationships. Significant social changes occurred during our period of analysis, including changing human ignitions, fuel manipulation and the decrease of Indigenous fire management (Swetnam et al. 2016; Stambaugh et al. 2018; Roos et al. 2021), but these changes were highly variable in space and time. For example, Indigenous fire management reduced the top-down influence of climate on fire in multiple locations during specific time periods in the southwestern United States (Roos et al. 2022), Sierra Nevada (Taylor et al. 2016) and the Great Lakes (Kipfmueller et al. 2021). The contrasting trends we found in fire-climate relationships at the subregional scale (e.g., increasing strength through time in the Black Hills and decreasing in the Northern Forests, Figure 7) likely reflect the spatial variability of these bottom-up factors. The qualitative temporal changes in the strength of fire-climate relationships that occurred in many regions and subregions from circa 1800 to 1840 (Figure 7) likely reflects both climate and human influences. This period includes major volcanic eruptions that influenced global climate (e.g., Tambora, Indonesia in 1815) and promoted cooling associated with the Little Ice Age in North America (Stoffel et al. 2015; King et al. 2024). In the southwest region, the early 1800s was also identified as a time of reduced fire activity, possibly associated with less ENSO variability (Swetnam and Betancourt 1998), but there was also likely varying human influences on fire during this period (e.g., Baisan and Swetnam 1997).

4.3 | Effects and Responses to Climate-Driven Widespread Fire

Our results suggest that widespread synchronous fire driven by climate was historically common in many forested regions of North America, and given projected warming, will likely continue into the future with effects on societies and ecosystems (e.g., record-breaking fires across Canada in 2023). Increasingly widespread and severe contemporary fires are altering carbon and water storage and regulation (Hurteau et al. 2014; Williams et al. 2022), threatening public health (Reid et al. 2016; Burke et al. 2021), and reducing wildlife habitat for threatened and endangered species (Jones et al. 2020; Steel et al. 2023). Moreover, synchronous fire activity strains firefighting resources, overwhelms fire suppression efforts and causes profound societal disruption (Abatzoglou et al. 2021; Higuera et al. 2023). The fires reported in this paper were reconstructed from tens of thousands of scars resulting from low-severity fires that did not kill the sampled trees. Many of these same forests are now burning at uncharacteristically high severity (Hagmann et al. 2021; Parks et al. 2023) due in-part to the accumulation of a century or more of fuels (Haugo et al. 2019; Williams et al. 2023), exacerbated by climate change (Parisien et al. 2023). When these severe fires are followed by climatic conditions that limit seedling establishment and survival (Davis et al. 2019), forests are converted to non-forest vegetation (Coop et al. 2020). Societal responses to try to minimise socio-ecological effects of increasing widespread fire span multiple spatial scales from reducing global greenhouse gas emissions to minimise warming, to local to regional fire and fuels management that can buffer societal effects and resist or direct ecosystem changes (sensu Schuurman et al. 2020).

4.4 | Methodological and Data Limitations and Next Steps

A limitation of our approach is the varying spatial coverage of long, replicated tree-ring fire-scar chronologies across the continent (Figure 1). Fire-scar site density is highest in western North American forests, while there are large data gaps in other regions (e.g., Canada, Alaska, southern Mexico and the southeastern United States). These spatial imbalances in the data could partly explain some of the variability in the strength of fire-climate relationships, particularly in eastern and northern regions. Poor correlations between fire and soil moisture may also reflect the lower skill of the climate reconstruction outside of western North America (Williams et al. 2020). We chose June–August soil moisture to represent fire-season climate because this is the peak of summer in North America when temperature and drought effects on fuels are strongest in most forests. However, this time period is seasonally wet and has relatively low fire activity in some locations, such as the eastern United States and the monsoon region of southern North America, where fire is more likely to occur before or after the rainy season (Arizpe et al. 2020; Margolis et al. 2022; Lafon et al. 2017), potentially leading to a temporal mismatch. Next steps to improve our understanding of the fire-climate system include: (1) fine-tuning the season of climate variables (e.g., spring vs. summer vs. fall) that have the strongest relationship with historical fire occurrence in the different subregions, (2) using new palaeoclimate reconstructions (e.g., King et al. 2024) to better understand the influence of temperature on fire and (3) testing for spatial stability of historical climate and fire regions by comparing them with contemporary climate and fire patterns.

5 | Conclusions

We found that spatially coherent climate patterns were strongly associated with widespread synchronous fire occurrence at multiple spatial scales across North American forests. No single spatial scale encompassed the full range of climate influence on fire patterns. The subregional scale may have the most utility for application to future forecasting and wildfire management, due to the relatively high within-group fire synchrony and strong fire-climate relationships in many locations. The subregions we produced should also be useful to group other independent variables for future climate and fire research, similar to fire 'pyrome' classifications. On the other hand, the broader-scale regions we identified highlight vast areas of climate and fire synchrony more influenced by synoptic patterns of atmospheric circulation. These historical patterns suggest that recent synchrony of fire across large areas entrained by climate is not unprecedented and will likely continue into the future, exhibiting consistent spatial patterns.

Acknowledgements

Funding was provided by the USGS John Wesley Powell Center for Analysis and Synthesis, the USGS Ecosystems Land Change Science Program, USGS Southwest Climate Adaptation Science Center, the Gordon and Betty Moore Foundation, and the Sustainable LA Grand Challenges Program. T.W. Swetnam, M. Krawchuk, N. Tutland, the associate editor and an anonymous reviewer provided ideas and comments that improved the manuscript. The statements, findings, conclusions and recommendations are those of the author(s) and do not necessarily reflect the views of NOAA or the US Department of Commerce. Any use of trade, firm or product names is for descriptive purposes only and does not imply endorsement by the US Government.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data and code for reproducing these analyses are available here: https://doi.org/10.5061/dryad.280gb5mxh. The research team consists of a diverse group of dendrochronologists and fire, forest and climate scientists from across the United States and Canada.

References

Abatzoglou, J. T., C. S. Juang, A. P. Williams, C. A. Kolden, and A. L. Westerling. 2021. "Increasing Synchronous Fire Danger in Forests of the Western United States." *Geophysical Research Letters* 48: e2020GL091377.

Abatzoglou, J. T., and C. A. Kolden. 2013. "Relationships Between Climate and Macroscale Area Burned in the Western United States." *International Journal of Wildland Fire* 22: 1003–1020.

Abatzoglou, J. T., and A. P. Williams. 2016. "Impact of Anthropogenic Climate Change on Wildfire Across Western US Forests." *Proceedings of the National Academy of Sciences* 113: 11770–11775.

Aldrich, S. R., C. W. Lafon, H. D. Grissino-Mayer, G. G. DeWeese, and J. Williams. 2014. "Fire History and Its Relations With Land Use and Climate Over Three Centuries in the Central Appalachian Mountains, USA." *Journal of Biogeography* 41: 2093–2104.

Archibald, S., C. E. Lehmann, J. L. Gomez-Dans, and R. A. Bradstock. 2013. "Defining Pyromes and Global Syndromes of Fire Regimes." *Proceedings of the National Academy of Sciences of the United States of America* 110: 6442–6447.

Arizpe, A. H., D. A. Falk, C. A. Woodhouse, and T. W. Swetnam. 2020. "Widespread Fire Years in the US–Mexico Sky Islands Are Contingent on Both Winter and Monsoon Precipitation." *International Journal of Wildland Fire* 29: 1072.

Badr, H. S., B. F. Zaitchik, and A. K. Dezfuli. 2015. "A Tool for Hierarchical Climate Regionalization." *Earth Science Informatics* 8: 949–958.

Bai, H., C. Strong, and B. Zuckerberg. 2023. "Drivers of an Ecologically Relevant Summer North American Dipole." *Journal of Climate* 36: 2387–2399.

Baisan, C. H., and T. W. Swetnam. 1997. "Interactions of Fire Regimes and Land Use in the Central Rio Grande Valley." Rocky Mountain Forest and Range Experiment Station, Research Paper RM-RP-330, USDA Forest Service, Fort Collins, CO, 1–20.

Balch, J. K., B. A. Bradley, J. T. Abatzoglou, R. C. Nagy, E. J. Fusco, and A. L. Mahood. 2017. "Human-Started Wildfires Expand the Fire Niche Across the United States." *Proceedings of the National Academy of Sciences of the United States of America* 114: 2946–2951.

Boulanger, Y., S. Gauthier, and P. J. Burton. 2014. "A Refinement of Models Projecting Future Canadian Fire Regimes Using Homogeneous Fire Regime Zones." *Canadian Journal of Forest Research* 44: 365–376.

Brown, P. M., and R. Wu. 2005. "Climate and Disturbance Forcing of Episodic Tree Recruitment in a Southwestern Ponderosa Pine Landscape." *Ecology* 86: 3030–3038.

Burke, M., A. Driscoll, S. Heft-Neal, J. Xue, J. Burney, and M. Wara. 2021. "The Changing Risk and Burden of Wildfire in the United States." *Proceedings of the National Academy of Sciences of the United States of America* 118: e2011048118.

Campos-Ruiz, R., M.-A. Parisien, and M. Flannigan. 2018. "Temporal Patterns of Wildfire Activity in Areas of Contrasting Human Influence in the Canadian Boreal Forest." *Forests* 9, no. 4: 15.

Cardil, A., M. Rodrigues, M. Tapia, et al. 2023. "Climate Teleconnections Modulate Global Burned Area." *Nature Communications* 14: 427.

Cattau, M., A. Mahood, J. Balch, and C. Wessman. 2022. "Modern Pyromes: Biogeographical Patterns of Fire Characteristics Across the Contiguous United States." *Fire* 5: 95.

Chavardès, R. D., L. D. Daniels, J. E. Harvey, et al. 2021. "Regional Drought Synchronised Historical Fires in Dry Forests of the Montane Cordillera Ecozone, Canada." *International Journal of Wildland Fire* 31: 67–80.

Cheal, A. J., S. Delean, H. Sweatman, and A. A. Thompson. 2007. "Spatial Synchrony in Coral Reef Fish Populations and the Influence of Climate." *Ecology* 88: 158–169.

Comrie, A. C., and E. C. Glenn. 1998. "Principal Components-Based Regionalization of Precipitation Regimes Across the Southwest United States and Northern Mexico, With an Application to Monsoon Precipitation Variability." *Climate Research* 10: 201–215.

Cook, B. I., T. R. Ault, and J. E. Smerdon. 2015. "Unprecedented 21st Century Drought Risk in the American Southwest and Central Plains." *Science Advances* 1: e1400082.

Cook, E. R., C. A. Woodhouse, and C. M. Eakin. 2004. "Long-Term Aridity Changes in the Western United States." *Science* 306: 1015–1018.

Coop, J. D., S. A. Parks, C. S. Stevens-Rumann, et al. 2020. "Wildfire-Driven Forest Conversion in Western North American Landscapes." *Bioscience* 70: 659–673.

Copes-Gerbitz, K., L. D. Daniels, and S. M. Hagerman. 2023. "The Contribution of Indigenous Stewardship to an Historical Mixed-Severity Fire Regime in British Columbia, Canada." *Ecological Applications* 33: e2736.

Dannenberg, M. P., and E. K. Wise. 2017. "Shifting Pacific Storm Tracks as Stressors to Ecosystems of Western North America." *Global Change Biology* 23: 4896–4906.

Davis, K. T., S. Z. Dobrowski, P. E. Higuera, et al. 2019. "Wildfires and Climate Change Push Low-Elevation Forests Across a Critical Climate Threshold for Tree Regeneration." *Proceedings of the National Academy of Sciences of the United States of America* 116: 6193–6198.

Eidenshink, J. C., B. Schwind, K. Brewer, Z. Zhu, B. Quayle, and S. Howard. 2007. "A Project for Monitoring Trends in Burn Severity." *Fire Ecology* 3: 3–21.

Erni, S., X. Wang, S. Taylor, et al. 2019. "Developing a Two-Level Fire Regime Zonation System for Canada." *Canadian Journal of Forest Research* 50: 259–273.

Falk, D. A., C. Miller, D. McKenzie, and A. E. Black. 2007. "Cross-Scale Analysis of Fire Regimes." *Ecosystems* 10: 809–823.

Foster, A. C., J. K. Shuman, B. M. Rogers, et al. 2022. "Bottom-Up Drivers of Future Fire Regimes in Western Boreal North America." *Environmental Research Letters* 17: 025006.

Fulé, P. Z., L. L. Yocom, C. C. Montano, D. A. Falk, J. Cerano, and J. Villanueva-Diaz. 2012. "Testing a Pyroclimatic Hypothesis on the Mexico-United States Border." *Ecology* 93: 1830–1840.

Fye, F. K., D. W. Stahle, and E. R. Cook. 2003. "Paleoclimatic Analogs to Twentieth-Century Moisture Regimes Across the United States." *Bulletin of the American Meteorological Society* 84: 901–909.

Gershunov, A., and T. P. Barnett. 1998. "Interdecadal Modulation of ENSO Teleconnections." *Bulletin of the American Meteorological Society* 79: 2715–2725.

Gill, L., and A. H. Taylor. 2009. "Top-Down and Bottom-Up Controls on Fire Regimes Along an Elevational Gradient on the East Slope of the Sierra Nevada, California, USA." *Fire Ecology* 5: 57–75.

Girardin, M. P., J. C. Tardif, M. D. Flannigan, and Y. Bergeron. 2006. "Synoptic-Scale Atmospheric Circulation and Boreal Canada Summer Drought Variability of the Past Three Centuries." *Journal of Climate* 19: 1922–1947.

Guyette, R. P., R. M. Muzika, and D. C. Dey. 2002. "Dynamics of an Anthropogenic Fire Regime." *Ecosystems* 5: 472–486.

Hagmann, R. K., P. F. Hessburg, S. J. Prichard, et al. 2021. "Evidence for Widespread Changes in the Structure, Composition, and Fire Regimes of Western North American Forests." *Ecological Applications* 31, no. 8: e02431.

Hansen, M. C., P. V. Potapov, A. H. Pickens, et al. 2022. "Global Land Use Extent and Dispersion Within Natural Land Cover Using Landsat Data." *Environmental Research Letters* 17: 034050.

Hargrove, W. W., F. M. Hoffman, and P. F. Hessburg. 2006. "Mapcurves: A Quantitative Method for Comparing Categorical Maps." *Journal of Geographical Systems* 8: 187–208.

Harvey, J. E., and D. J. Smith. 2017. "Interannual Climate Variability Drives Regional Fires in West Central British Columbia, Canada." *Journal of Geophysical Research: Biogeosciences* 122: 1759–1774.

Haugo, R. D., B. S. Kellogg, C. A. Cansler, et al. 2019. "The Missing Fire: Quantifying Human Exclusion of Wildfire in Pacific Northwest Forests, USA." *Ecosphere* 10: e02702.

Heyerdahl, E. K., D. McKenzie, L. D. Daniels, A. E. Hessl, J. S. Littell, and N. J. Mantua. 2008. "Climate Drivers of Regionally Synchronous Fires in the Inland Northwest (1651-1900)." *International Journal of Wildland Fire* 17: 40–49.

Higuera, P. E., M. C. Cook, J. K. Balch, E. N. Stavros, A. L. Mahood, and L. A. St Denis. 2023. "Shifting Social-Ecological Fire Regimes Explain Increasing Structure Loss From Western Wildfires." *PNAS Nexus* 2: pgad005.

Hoffman, K. M., K. P. Lertzman, and B. M. Starzomski. 2017. "Ecological Legacies of Anthropogenic Burning in a British Columbia Coastal Temperate Rain Forest." *Journal of Biogeography* 44: 2903–2915.

Howard, L. F., G. D. Cahalan, K. Ehleben, B. A. Muhammad El, H. Halza, and S. DeLeon. 2021. "Fire History and Dendroecology of Catoctin Mountain, Maryland, USA, With Newspaper Corroboration." *Fire Ecology* 17: 8.

Hurteau, M. D., J. B. Bradford, P. Z. Fulé, A. H. Taylor, and K. L. Martin. 2014. "Climate Change, Fire Management, and Ecological Services in the Southwestern US." *Forest Ecology and Management* 327: 280–289.

Jain, P., and M. Flannigan. 2021. "The Relationship Between the Polar Jet Stream and Extreme Wildfire Events in North America." *Journal of Climate* 34: 1–59.

Johnson, L. B., and K. F. Kipfmueller. 2016. "A Fire History Derived From *Pinus resinosa* Ait. For the Islands of Eastern Lac La Croix, Minnesota, USA." *Ecological Applications* 26: 1030–1046.

Johnston, J. D., M. R. Schmidt, A. G. Merschel, W. M. Downing, M. R. Coughlan, and D. G. Lewis. 2023. "Exceptional Variability in Historical Fire Regimes Across a Western Cascades Landscape, Oregon, USA." *Ecosphere* 14: e4735.

Jones, G. M., R. J. Gutiérrez, W. M. Block, et al. 2020. "Spotted Owls and Forest Fire: Comment." *Ecosphere* 11: 11.

Kiladis, G., and H. F. Diaz. 1989. "Global Climatic Anomalies Associated With Extremes in the Southern Oscillation." *Journal of Climate* 2: 169–190.

King, K. E., E. R. Cook, K. J. Anchukaitis, et al. 2024. "Increasing Prevalence of Hot Drought Across Western North America Since the 16th Century." *Science Advances* 10: eadj4289.

Kipfmueller, K. F., E. R. Larson, L. B. Johnson, and E. A. Schneider. 2021. "Human Augmentation of Historical Red Pine Fire Regimes in the Boundary Waters Canoe Area Wilderness." *Ecosphere* 12: e03673.

Kipfmueller, K. F., E. A. Schneider, S. A. Weyenberg, and L. B. Johnson. 2017. "Historical Drivers of a Frequent Fire Regime in the Red Pine Forests of Voyageurs National Park, MN, USA." *Forest Ecology and Management* 405: 31–43.

Kitzberger, T., P. M. Brown, E. K. Heyerdahl, T. W. Swetnam, and T. T. Veblen. 2007. "Contingent Pacific-Atlantic Ocean Influence on Multicentury Wildfire Synchrony Over Western North America." *Proceedings of the National Academy of Sciences of the United States of America* 104: 543–548.

Koenig, W. D., and A. M. Liebhold. 2016. "Temporally Increasing Spatial Synchrony of North American Temperature and Bird Populations." *Nature Climate Change* 6: 614–617.

Köppen, W. 2011. "The Thermal Zones of the Earth According to the Duration of Hot, Moderate and Cold Periods and to the Impact of Heat on the Organic World." *Meteorologische Zeitschrift* 20: 351–360.

Lafon, C. W., A. T. Naito, H. Grissino-Mayer, S. P. Horn, and T. A. Waldrop. 2017. *Fire History of the Appalachian Region: A Review and Synthesis*. Asheville, NC: USDA Forest Service Southern Research Station, General Technical Report SRS-219.

LaMontagne, J. M., I. S. Pearse, D. F. Greene, and W. D. Koenig. 2020. "Mast Seeding Patterns Are Asynchronous at a Continental Scale." *Nature Plants* 6: 460–465.

Littlefield, C. E., S. Z. Dobrowski, J. T. Abatzoglou, S. A. Parks, and K. T. Davis. 2020. "A Climatic Dipole Drives Short- and Long-Term Patterns of Postfire Forest Recovery in the Western United States." *Proceedings of the National Academy of Sciences of the United States of America* 117: 29730–29737.

Macias Fauria, M., and E. A. Johnson. 2008. "Climate and Wildfires in the North American Boreal Forest." *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 363: 2317–2329.

Malevich, S. B., C. H. Guiterman, and E. Q. Margolis. 2018. "Burnr: Fire History Analysis and Graphics in R." *Dendrochronologia* 49: 9–15.

Mann, M. E., S. Rahmstorf, K. Kornhuber, et al. 2018. "Projected Changes in Persistent Extreme Summer Weather Events: The Role of Quasi-Resonant Amplification." *Science Advances* 4: eaat3272.

Margolis, E. Q., C. H. Guiterman, R. D. Chavardès, et al. 2022. "The North American Tree-Ring Fire-Scar Network." *Ecosphere* 13: e4159.

Marschall, J. M., M. C. Stambaugh, B. C. Jones, and E. Abadir. 2019. "Spatial Variability of Historical Fires Across a Red Pine–Oak Landscape, Pennsylvania, USA." *Ecosphere* 10: e02978.

McCabe, G. J., M. A. Palecki, and J. L. Betancourt. 2004. "Pacific and Atlantic Ocean Influences on Multidecadal Drought Frequency in the United States." *Proceedings of the National Academy of Sciences of the United States of America* 101: 4136–4141.

Meko, D., E. R. Cook, D. W. Stahle, C. W. Stockton, and M. K. Hughes. 1993. "Spatial Patterns of Tree-Growth Anomalies in the United States and Southeastern Canada." *Journal of Climate* 6: 1773–1786.

Meunier, J., W. H. Romme, and P. M. Brown. 2014. "Climate and Land-Use Effects on Wildfire in Northern Mexico, 1650-2010." *Forest Ecology and Management* 325: 49–59.

Meyn, A., S. W. Taylor, M. D. Flannigan, K. Thonicke, and W. Cramer. 2010. "Relationship Between Fire, Climate Oscillations, and Drought in British Columbia, Canada, 1920–2000." *Global Change Biology* 16: 977–989.

Morgan, P., E. K. Heyerdahl, and C. E. Gibson. 2008. "Multi-Season Climate Synchronized Forest Fires Throughout the 20th Century, Northern Rockies, U.S.A." *Ecology* 89: 717–728.

Murtagh, F., and P. Legendre. 2014. "Ward's Hierarchical Agglomerative Clustering Method: Which Algorithms Implement Ward's Criterion?" *Journal of Classification* 31: 274–295.

NIFC. 2024. "National Interagency Fire Center." https://www.nifc.gov/.

Nowosad, J., and T. F. Stepinski. 2018. "Spatial Association Between Regionalizations Using the Information-Theoretical V-Measure." *International Journal of Geographical Information Science* 32: 2386–2401.

Osman, M. B., S. Coats, S. B. Das, J. R. McConnell, and N. Chellman. 2021. "North Atlantic Jet Stream Projections in the Context of the Past 1,250 Years." *Proceedings of the National Academy of Sciences of the United States of America* 118: e2104105118.

Parisien, M.-A., Q. E. Barber, M. L. Bourbonnais, et al. 2023. "Abrupt, Climate-Induced Increase in Wildfires in British Columbia Since the Mid-2000s." *Communications Earth & Environment* 4: 309.

Parks, S. A., L. M. Holsinger, K. Blankenship, G. K. Dillon, S. A. Goeking, and R. Swaty. 2023. "Contemporary Wildfires Are More Severe Compared to the Historical Reference Period in Western US Dry Conifer Forests." *Forest Ecology and Management* 544: 544.

Parks, S. A., M.-A. Parisien, and C. Miller. 2012. "Spatial Bottom-Up Controls on Fire Likelihood Vary Across Western North America." *Ecosphere* 3: 1–20.

Pascale, S., W. R. Boos, S. Bordoni, et al. 2017. "Weakening of the North American Monsoon With Global Warming." *Nature Climate Change* 7: 806–812.

Post, E., and M. C. Forchhammer. 2002. "Synchronization of Animal Population Dynamics by Large-Scale Climate." *Nature* 420: 168–171.

R Core Team. 2022. *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing.

Reid, C. E., M. Brauer, F. H. Johnston, M. Jerrett, J. R. Balmes, and C. T. Elliott. 2016. "Critical Review of Health Impacts of Wildfire Smoke Exposure." *Environmental Health Perspectives* 124: 1334–1343.

Roos, C. I., C. H. Guiterman, E. Q. Margolis, et al. 2022. "Indigenous Fire Management and Cross-Scale Fire-Climate Relationships in the Southwest United States From 1500 to 1900 CE." *Science Advances* 8: eabq3221.

Roos, C. I., T. W. Swetnam, T. J. Ferguson, et al. 2021. "Native American Fire Management at an Ancient Wildland-Urban Interface in the Southwest United States." *Proceedings of the National Academy of Sciences of the United States of America* 118: 118.

Schroeder, M. J., and C. J. Buck. 1970. "Fire Weather: A Guide for Application of Meteorological Information to Forest Fire Control Operations." *USDA Forest Service, Agriculture Handbook 360*.

Schuurman, G. W., C. H. Hoffman, D. N. Cole, et al. 2020. *Resist-Accept-Direct (RAD)—A Framework for the 21st-Century Natural Resource Manager*. Fort Collins, CO: National Park Service.

Stambaugh, M. C., J. M. Marschall, E. R. Abadir, et al. 2018. "Wave of Fire: An Anthropogenic Signal in Historical Fire Regimes Across Central Pennsylvania, USA." *Ecosphere* 9: e02222.

Steel, Z. L., G. M. Jones, B. M. Collins, et al. 2023. "Mega-Disturbances Cause Rapid Decline of Mature Conifer Forest Habitat in California." *Ecological Applications* 33: e2763.

Stoffel, M., M. Khodri, C. Corona, et al. 2015. "Estimates of Volcanic-Induced Cooling in the Northern Hemisphere Over the Past 1,500 Years." *Nature Geoscience* 8: 784–788.

Sutheimer, C. M., J. Meunier, I. Drobyshev, et al. 2023. "Climate Forcing of Regional Fire Years in the Upper Great Lakes Region, USA." *International Journal of Wildland Fire* 32: 796–813.

Swetnam, T. W., C. D. Allen, and J. L. Betancourt. 1999. "Applied Historical Ecology: Using the Past to Manage for the Future." *Ecological Applications* 9: 1189–1206.

Swetnam, T. W., and C. H. Baisan. 1996. "Historical Fire Regime Patterns in the Southwestern United States Since AD 1700." *Proceedings of the 2nd La Mesa Fire Symposium*, 11–32. Los Alamos, NM. Fort Collins, CO: USDA Forest Service Rocky Mountain Forest and Range Experiment Station. RM-GTR-286.

Swetnam, T. W., and J. L. Betancourt. 1990. "Fire-Southern Oscillation Relations in the Southwestern United States." *Science* 249: 1017–1020.

Swetnam, T. W., and J. L. Betancourt. 1998. "Mesoscale Disturbance and Ecological Response to Decadal Climatic Variability in the American Southwest." *Journal of Climate* 11: 3128–3147.

Swetnam, T. W., J. Farella, C. I. Roos, M. J. Liebmann, D. A. Falk, and C. D. Allen. 2016. "Multi-Scale Perspectives of Fire, Climate and Humans in Western North America and the Jemez Mountains, USA." *Proceedings of the Royal Society of London, Series B: Biological Sciences* 371: 20150168.

Taylor, A. H., V. Trouet, C. N. Skinner, and S. Stephens. 2016. "Socioecological Transitions Trigger Fire Regime Shifts and Modulate Fire-Climate Interactions in the Sierra Nevada, USA, 1600–2015 CE." *Proceedings of the National Academy of Sciences of the United States of America* 113: 13684–13689.

Trouet, V., A. H. Taylor, E. R. Wahl, C. N. Skinner, and S. L. Stephens. 2010. "Fire-Climate Interactions in the American West Since 1400 CE." *Geophysical Research Letters* 37: L04702.

Tulowiecki, S. J., B. B. Hanberry, and M. D. Abrams. 2023. "Native American Geography Shaped Historical Fire Frequency in Forests of Eighteenth-Century Pennsylvania, USA." *Scientific Reports* 13: 18598.

Turco, M., J. T. Abatzoglou, S. Herrera, et al. 2023. "Anthropogenic Climate Change Impacts Exacerbate Summer Forest Fires in California." *Proceedings of the National Academy of Sciences of the United States of America* 120: e2213815120.

Wahl, E. R., E. Zorita, V. Trouet, and A. H. Taylor. 2019. "Jet Stream Dynamics, Hydroclimate, and Fire in California From 1600 CE to Present." *Proceedings of the National Academy of Sciences of the United States of America* 116: 5393–5398.

Walker, X. J., J. L. Baltzer, S. G. Cumming, et al. 2019. "Increasing Wildfires Threaten Historic Carbon Sink of Boreal Forest Soils." *Nature* 572: 520–523.

Walter, J. A., L. W. Sheppard, T. L. Anderson, et al. 2017. "The Geography of Spatial Synchrony." *Ecology Letters* 20: 801–814.

White, D., M. B. Richman, and B. Yarnal. 1991. "Climate Regionalization and Rotation of Principal Components." *International Journal of Climatology* 11: 1–25.

Williams, A. P., B. I. Cook, and J. E. Smerdon. 2022. "Rapid Intensification of the Emerging Southwestern North American Megadrought in 2020–2021." *Nature Climate Change* 12: 232–234.

Williams, A. P., E. R. Cook, J. E. Smerdon, et al. 2020. "Large Contribution From Anthropogenic Warming to an Emerging North American Megadrought." *Science* 368: 314–318.

Williams, A. P., B. Livneh, K. A. McKinnon, et al. 2022. "Growing Impact of Wildfire on Western US Water Supply." *Proceedings of the National Academy of Sciences of the United States of America* 119: e2114069119.

Williams, J. N., H. D. Safford, N. Enstice, Z. L. Steel, and A. K. Paulson. 2023. "High-Severity Burned Area and Proportion Exceed Historic Conditions in Sierra Nevada, California, and Adjacent Ranges." *Ecosphere* 14: e4397.

Woodhouse, C. A., D. M. Meko, G. M. MacDonald, D. W. Stahle, and E. R. Cook. 2010. "A 1,200-Year Perspective of 21st Century Drought in Southwestern North America." *Proceedings of the National Academy of Sciences of the United States of America* 107: 21283–21288.

Yarnal, B. 1993. *Eigenvector-Based Classifications*, 73–107. London, England: Belhaven press.

Yocom Kent, L. L., P. Z. Fulé, P. M. Brown, et al. 2017. "Climate Drives Fire Synchrony but Local Factors Control Fire Regime Change in Northern Mexico." *Ecosphere* 8: e01709.

Yocom, L. L., P. Z. Fulé, P. M. Brown, et al. 2010. "El Nino-Southern Oscillation Effect on a Fire Regime in Northeastern Mexico Has Changed Over Time." *Ecology* 91: 1660–1671.

Zhang, Y., J. Fan, M. Shrivastava, C. R. Homeyer, Y. Wang, and J. H. Seinfeld. 2022. "Notable Impact of Wildfires in the Western United States on Weather Hazards in the Central United States." *Proceedings of the National Academy of Sciences of the United States of America* 119: e2207329119.

Zhao, B., Q. Zhuang, N. Shurpali, K. Koster, F. Berninger, and J. Pumpanen. 2021. "North American Boreal Forests Are a Large Carbon Source due to Wildfires From 1986 to 2016." *Scientific Reports* 11: 7723.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.