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Wildfire activity in northern Rocky Mountain subalpine forests still within millennial-scale range of variability

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Abstract

Increasing area burned across western North America raises questions about the precedence and magnitude of changes in fire activity, relative to the historical range of variability (HRV) that ecosystems experienced over recent centuries and millennia. Paleoecological records of past fire occurrence provide context for contemporary changes in ecosystems characterized by infrequent, high-severity fire regimes. Here we present a network of 12 fire-history records derived from macroscopic charcoal preserved in sediments of small subalpine lakes within a c. 10 000 km^2 landscape in the U.S. northern Rocky Mountains (Northern Rockies). We used this network to characterize landscape-scale burning over the past 2500 yr, and to evaluate the precedence of widespread regional burning experienced in the early 20th and 21st centuries. We further compare the Northern Rockies fire history to a previously published network of fire-history records in the Southern Rockies. In Northern Rockies subalpine forests, widespread fire activity was strongly linked to seasonal climate conditions, in contemporary, historical, and paleo records. The average estimated fire rotation period (FRP) over the past 2500 yr was 164 yr (HRV: 127–225 yr), while the contemporary FRP from 1900 to 2021 CE was 215 yr. Thus, extensive regional burning in the early 20th century (e.g. 1910 CE) and in recent decades remains within the HRV of recent millennia. Results from the Northern Rockies contrast with the Southern Rockies, which burned with less frequency on average over the past 2500 yr, and where 21st-century burning has exceeded the HRV. Our results support expectations that Northern Rockies fire activity will continue to increase with climatic warming, surpassing historical burning if more than one exceptional fire year akin to 1910 occurs within the next several decades. The ecological consequences of climatic warming in subalpine forests will depend, in large part, on the magnitude of fire-regime changes relative to the past.

1. Introduction

Fire activity is increasing across western North America, in part due to the impacts of anthropogenic climate change [1–3], and is expected to continue to increase under future climate [4–6]. Warmer and drier conditions increase fuel aridity, which enables extensive burning by making fuels more susceptible to ignition and rapid fire spread [1, 7–9]. Increased fire activity in high-elevation forests across the western US has been especially pronounced, as widespread burning in these forests is typically limited by high fuel moisture and short fire seasons [10]. Higher fire activity in turn has wide-ranging impacts on species turnover, water resources, and human communities [11–13].

Understanding the causes and consequences of past variability in fire activity—the historical range of variability (HRV)—helps frame ongoing change and anticipate potential ecological and societal implications of future increases in fire activity [14]. The HRV represents conditions ecosystems have developed with over centuries to millennia, and it implicitly reflects dynamics that have maintained ecosystems, and ecosystem resilience to wildfire and other environmental changes [e.g. 15]. Comparing contemporary changes to those under the HRV is made complicated by direct human impacts on fire regimes, and by a lack of long-term datasets. Despite increases in area burned across the western U.S. in recent decades, for example, there is evidence of a 'fire deficit' over the past one to two centuries as a result of reduced Indigenous fire stewardship, land use intensification, and fire suppression [16, 17]. Additionally, in ecosystems characterized by high-severity fire regimes (i.e., fires causing high tree mortality, occurring on average once every >100 yr), observational and dendrochronological fire-history records only capture one to several fires at any given site.

Paleoecological archives from lake-sediment records provide opportunities to quantify past variability in fire activity over centuries to millennia [18]. High-resolution records of macroscopic charcoal particles (e.g. >125 μm diameter) preserved in lake sediments, sampled continuously at (sub-)decadal time intervals, can be used to reconstruct past fire events through the identification of distinct peaks in charcoal accumulation [19, 20]. Peaks in macroscopic charcoal, primarily dispersed through airborne fallout, typically reflect fire events occurring within 0.5–1 km of a lake, representing an area of one to several square kilometers [20–22]. The fire history from any individual lake-sediment record is unlikely to reflect variations in fire activity that span short timescales (e.g. centuries), due to the stochastic nature of fire occurrence [23, 24]. Combining multiple lake-sediment records to form a spatially dense network of sites is thus necessary to detect changes in fire activity at landscape to regional scales [e.g. 21, 25, 26].

Densely sampled networks of lake-sediment records in North American boreal [21] and subalpine [25] forest ecosystems demonstrate the sensitivity of fire activity to past centennial-scale climatic variation. Such networks have revealed increased landscape burning during a period of relative warmth c. 1000 yr ago (the Medieval Climate Anomaly, MCA), and they demonstrate that fire activity in recent decades has already exceeded the HRV of recent millennia in some regions [21, 26]. These studies highlight the pace and scale of emerging shifts in fire regimes accompanying contemporary climate change, and they underscore uncertainties about ecosystem responses to long-unprecedented climate warming [27]. As more regional fire histories are developed, it becomes possible to analyze the spatial scale of synchronous changes in fire regimes, identify regional differences, and understand possible drivers [28].

Here we present a densely sampled network of lake-sediment fire-history records from the U.S. northern Rocky Mountains (hereafter Northern Rockies), a region that has strongly contributed to trends in area burned in the western U.S. in recent decades [7, 29]. Fire activity in the Northern Rockies is elevated in years with early spring snowmelt and above-average spring and summer warmth and aridity [7, 30–32], as exemplified by widespread burning across c. 12 000 km^2 in Idaho and Montana in 1910. The 1910 fires, called 'The Big Burn', were enabled by a warm, dry spring and summer [31, 32], ignited by lightning, railroad sparks, and other human activities, and driven by a high wind event in August; these fires also helped set the stage for U.S. fire policies emphasizing fire suppression [33]. It has long been questioned to what degree early 20th-century burning, including 1910, was anomalous due to extensive Euro-American expansion, or consistent with longstanding variability in fire activity. This question remains relevant for anticipating the impacts of ongoing climate warming in the Northern Rockies, and it requires understanding the sensitivity of fire activity to climatic and anthropogenic drivers over centuries to millennia.

To provide context for ongoing and expected fire-regime changes in the Northern Rockies, we developed 12 lake-sediment records from within a c. 10 000 km^2 landscape in northern Idaho and western Montana [34]. We reconstructed a landscape-scale fire history spanning the past 2500 yr in subalpine forests, which are characterized by infrequent, high-severity fire regimes [35]. Our goals were to: (1) characterize the HRV of fire activity over the past 2500 yr; and (2) explicitly evaluate the precedence of early 20th-century and 21st-century fire activity within the context of recent millennia. We further compared historical and contemporary fire activity in the Northern Rockies with that of the Southern Rockies, to evaluate broad-scale regional synchrony, assess sensitivity to climatic variation, and provide context for ongoing changes. We predicted that, in alignment with the Southern Rockies, fire activity in the Northern Rockies would increase in response to warming during the Medieval Climate Anomaly (MCA; c. 1200–800 yr before 1950 CE, hereafter yr BP) and late-20th and early-21st century warming, relative to the average of the past several millennia. We discuss these findings in light of ongoing and expected climatic and fire-regime changes and their impacts on ecosystems and society.

2. Methods

2.1. Study area and contemporary fire history

We characterized contemporary and historical fire activity in subalpine forests in the Bitterroot Mountains ecoregion (M333D, figure 1) [36]. Subalpine forests in the region are dominated by *Picea engelmannii, Abies lasiocarpa*, and *Pinus contorta; Tsuga mertensiana* is common in the western part of the study area. Mean annual temperature and precipitation averaged 5.70 °C ± 0.68 (sd) and 1156 mm ± 161, respectively, over 1991–2020 [37]. Precipitation is snow-dominated, with 8% on average falling during the driest three months of July-September.

Modern fire history within the ecoregion was characterized using area burned from the Northern Rockies Fire Atlas (NRFA, 1900–2008) [38] and the Monitoring Trends in Burn Severity program (MTBS, 1984–2021) [39]. To ensure consistency between the two datasets, we used fires >405 ha from the NRFA, and we subset MTBS fire perimeters to the same federally managed lands represented in the NRFA. To assess fire-climate relationships, we used two sources of annual climate data: average summer maximum vapor pressure deficit (VPD) from PRISM for 1900–2021 and average summer VPD from gridMet for 1984–2021 (4 km^2 resolution) [37, 40]. Climate data were spatially averaged across the ecoregion (figure 1), and relationships with annual area burned were assessed using Spearman rank correlations.

To summarize 20th- and 21st-century fire regimes, we calculated fire rotation periods (FRPs), defined as the time it takes to burn an area equal in size to the study area: $\frac{t}{\sum a_i/A}$, where t is the time period evaluated, a_i is annual area burned in year i, and A is the size of the study area. We summarized FRP for the ecoregion overall, and for subalpine forest within the ecoregion, defined by vegetation classes from LANDFIRE's Environmental Site Potential product [41]. Additionally, we summarized the FRP separately for the 21st century and for time periods previously identified from the NRFA as having distinctly different rates of burning: 1900–1942, 1943–1984, and 1985–2021 [32].

2.2. Paleofire history and statistical analyses

To characterize historical fire regimes, we reconstructed fire histories from 12 lake-sediment records spanning a c. 10 000 km^2 landscape [34]. A total of 2–4 m of sediment was collected from each lake, between 2017 and 2019. Chronologies were constructed using the package *rbacon* in R (v. 4.2.1) [42, 43] based on a combination of ^{210}Pb-inferred ages ($n = 7$–15 per site), tephra layers ($n = 0$–3 per site), and ^{14}C ages of terrestrial macrofossils or charcoal ($n = 3$–6 per site) (table S2, figures S2 and S3). Sediment cores were subsampled contiguously at 0.5-cm intervals, and macroscopic charcoal (>125 μm) particles were extracted and counted in each subsample. Concentrations of macroscopic charcoal (# cm^{-3}), interpolated to a constant timestep of 10 yr across all sites, were used to calculate the charcoal accumulation rate (CHAR, # particles cm^{-2} yr^{-1}). Local fire events (i.e., one or more fires within c. 0.5–1 km of the lake during the 10-yr sampling interval [19, 20]) were inferred from peaks in CHAR, identified using *CharAnalysis* in MATLAB (Mathworks Inc.; figure S4) [44, 45]. All records were analyzed with the same parameters, using a 500-yr smoothing window to characterize 'background' CHAR trends, and identifying charcoal peaks as those exceeding the 99th percentile of the 'noise distribution' (appendix A).

To produce a composite record of fire history across the study landscape, we calculated the percent of sites burned within a moving 100-yr window centered on each 10-yr timestep, following methods of Hoecker *et al* [46]. We accounted for age uncertainty in the timing of inferred fire events by resampling the year assigned to each charcoal peak 1000 times. For each iteration, fire years were drawn randomly from a normal distribution with a standard deviation of 40 yr, approximating the standard deviations of calibrated radiocarbon dates (figure S1) [46]. We present the median value from the 1000 iterations, smoothed over 100 yr with a loess smoother, and we used the 5th and 95th percentiles to estimate 90% confidence intervals of the % sites burned per century. This analysis was restricted to the past 2500 yr, when at least seven sites were recording. Finally, to allow direct comparisons between the paleofire record and FRPs calculated from contemporary area-burned statistics, we used the percent-of-sites-burned metric to calculate the paleo FRP in each 100-yr window, as in Calder *et al* [25] and Higuera *et al* [26]. Analogous to the FRP calculated from area burned statistics, the paleo FRP represents the amount of time it takes to burn an area equal in size to the combined area recorded by all 12 lake-sediment records in the network.

To characterize changes in biomass burning, we developed a composite CHAR series, using standard methods implemented in the *paleofire* R package [47]. Individual CHAR records were rescaled through mini-max, Box-Cox, and *z*-score transformations. The resulting transformed CHAR timeseries were summarized in 10-yr non-overlapping bins and smoothed to 100 yr prior to compositing [48]. Confidence intervals were generated by bootstrap sampling from among the CHAR timeseries 1000 times [47].

We compared the fire history of the Northern Rockies with that of the Southern Rockies, based on

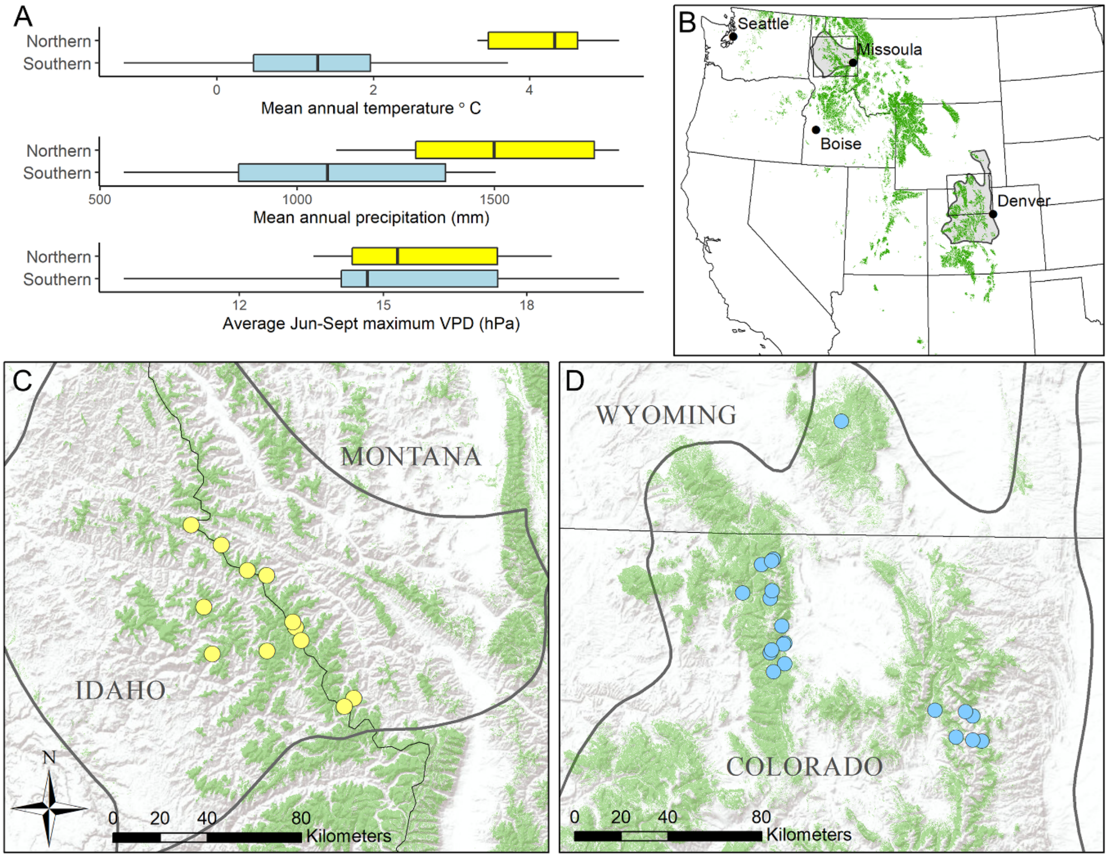

Figure 1. Map of northern and southern Rocky Mountain study regions and lake sites. (A): 30 yr average climate (1991–2020) from a 4 km grid cell centered on each lake site, for $n = 12$ lakes and $n = 20$ lakes in the Northern and Southern Rockies, respectively [37]. Climate variables include mean annual temperature, mean annual precipitation, and average daily maximum vapor pressure deficit (VPD) over June-September. (B): Focal ecoregions in the Northern and Southern Rockies (M333D and M331I/M331H) are outlined in grey, and boxes show the extent of each of the two study areas displayed in (C) and (D). The green shaded area delineates the potential extent of Rocky Mountain subalpine forest based on LandFire Environmental Site Potential [41]. (C), (D): Locations of lake sites in each of the two study regions, with $n = 12$ lakes in the Northern Rockies (C) and $n = 20$ lakes in the Southern Rockies (D). For analysis of relationships between VPD and annual area burned (figures 2 and S6), climate was spatially averaged across the entire ecoregion in each of the study regions (grey outlines in B).

contemporary area burned statistics and a network of 20 lake-sediment records previously summarized by Higuera *et al* [26], using paleofire data from the original sources [15, 25, 49]. We calculated the percent of sites burned per century and the paleo FRP (as described above) for all 20 records in the Southern Rockies network, and for a subset of 12 records from the Park Range in northwestern Colorado, within a landscape similar in size to the Northern Rockies study area (figure S5) [25].

We used several sources of paleoclimate information to compare to our fire history reconstructions. For broad-scale patterns over the past millennium, we drew on a multiproxy Northern Hemisphere temperature reconstruction [50], a pollen-based North America temperature reconstruction [51], and a reconstruction of ENSO variance based on North American tree-ring records [52]. Summer drought information in both study regions was obtained from tree-ring-based PDSI reconstructions [53]. Additional paleoclimate information specific to the Northern Rockies was derived from a previously published lake-level reconstruction from one of our study sites [54], an δ^{18}O-inferred snow water equivalent (SWE) reconstruction in northwest Montana [55], and a spatially-explicit summer temperature reconstruction [56]. To assess the strength of centennial-scale correlations between paleoclimate and fire activity, paleoclimate data were averaged over 100-yr moving windows, and time series were subset to one value every century and compared using Spearman rank correlations.

2.3. Fidelity of charcoal peaks to known fire history

A comparison between paleo-inferred and known fire histories from 1900 to 2021 CE revealed a lack of fidelity at four of the sites in the Northern Rockies, which recorded charcoal peaks that were younger than the most recent known fire at the site (table S3). We attribute this incongruence to the effects of partial mixing of flocculant sediments during collection and extrusion of surface cores. For the composite fire history analysis, we manually shifted the four anomalous fire dates to 1910, the date attributed in the NRFA [38]. This decision was based on radiocarbon measurements indicating that charcoal in the top-most layers predated c. 1950 (see details in appendix A). While the lack of congruence with the NRFA precludes a formal calibration study [e.g. 21], issues with sediment mixing are limited to flocculent near-surface sediments. Overall, we are confident in the accuracy of our fire history, given our use of a network of sites, which reduces the influence of inaccuracies at any one site, and the 100-yr precision of our analyses.

3. Results

3.1. 20th-21st century fire history in the Northern Rockies

Annual area burned in the Bitterroot Mountains ecoregion has increased significantly since 1984 (Sen's slope = 67.8 ha yr^{-1}, $p = 0.005$), consistent with previous studies documenting increased area burned across the Northern Rockies [29, 57]. The trend of increasing area burned since 1984 also applies when subalpine forests are considered alone (Sen's slope = 8.90 ha yr^{-1}, $p = 0.003$). Fire activity in recent decades has not exceeded that of the early 20th-century (table 1, figure 2). The vast majority of total area burned in the region occurred during years with regionally extensive fire activity, including 1910, 1919, and 2015, which alone account for 47%, 16%, and 4%, of total area burned, respectively. Within subalpine forest, the estimated FRP over 1900–2021 was 215 yr, but FRP estimates differed substantially among multidecadal periods (table 1). The FRP was 97 yr during the early 20th century (1900–1942), compared to 394 yr from 1984 to 2021 (figure 2). Higher fire activity in the past two decades contributed to a lower 21st-century (2000–2021) FRP of 237 yr.

Ecoregion-wide annual area burned was significantly correlated with annual maximum May-September VPD ($\rho = 0.58$, $p < 0.001$), a coarse proxy for fuel aridity [e.g. 58]. Fire-climate relationships varied over multidecadal time periods [32], with a weaker correlation during the middle of the 20th century ($\rho = 0.41$, $p = 0.007$; 1943–1983). Considering only 1984–2021, the Spearman correlation with average summer VPD was 0.55 ($p < 0.001$), lower than that in the Southern Rockies study area ($\rho = 0.75$, figure S6) [26].

3.2. Paleofire history in the Northern Rockies

Over the past 2500 yr, an average of 61% of the Northern Rockies sites burned in each 100 yr period, equivalent to an estimated FRP of 164 yr (figure 3). The 100-yr FRP estimates varied over time, with the central 75% ranging from 133 to 220 yr, providing a robust estimate of the HRV [26]. The range of FRP estimates overlap with mean fire-return-interval estimates from stand-origin and fire-scar analysis in four subalpine watersheds c. 100 km south of our study area, which range from 139 to 234 yr over 1527–2000 CE [59]. Over the same time span, an average of 53% of our sites burned per century, yielding an estimated FRP of 184 yr (central 75%: 133–300 yr). The percentage of sites burned per century over the past 2500 yr was weakly negatively correlated with average reconstructed April 1st SWE at Foy Lake, Montana, approximately 125 km northeast of our study area ($\rho = -0.43$, $p = 0.05$, $n = 22$ century periods after accounting for temporal autocorrelation; figures 4 and S7).

The highest rate of burning in the paleorecords occurred over c. 2300–2500 yr BP, with a maximum of 99% of sites burning during the century centered on 2410 yr BP, yielding an estimated FRP of 101 yr. The timing of maximum burning corresponds with a drop in lake level at Silver Lake, MT, one of our northernmost study sites (figure 4); although consistent with increased aridity, the timing of the drop in lake level is not precisely constrained [54]. The period with minimum burning spanned c. 100–250 yr BP, with an average of 25% of sites burning per century (FRP = 400 yr). The period of minimum burning overlapped with a local maximum in SWE, which averaged 0.87 sd above the long-term mean during the century centered on 210 yr BP. Burning increased in the early 20th century, reaching a recent maximum of 75% sites burned during the period 1850–1950 CE (FRP = 133 yr).

3.3. Fire-history comparison of the Northern and Southern Rockies

Across most of the record, the Northern Rockies landscape experienced higher fire activity than in the Southern Rockies region (figure 5). The average paleo-inferred FRP from the Southern Rockies sites was 239 yr, with the central 75% ranging from 196 to 333 yr. Although the HRV of each of the two regions overlapped, the series-wide estimated FRP represents 45% more burning per unit time on average in the Northern Rockies study area over the past 2500 yr.

In contrast to the average of the past 2500 yr, the Southern Rockies have experienced substantially higher fire activity over the 21st century compared with the Northern Rockies, largely due to the exceptional fire year of 2020. The 2000–2020 FRP of 117 yr in subalpine forests of the Southern Rockies exceeds the HRV of the past 2500 yr, and it also exceeds both contemporary burning and the HRV of the Northern Rockies (figure 5).

Although both regions have strong fire-climate linkages over the contemporary record (figure S6), past variability in fire activity was not synchronous (figure 5). Minima in fire activity occurred at different times in the two regions, but reflected similar FRPs of 400 yr. In contrast, maximum burning in the Northern Rockies (FRP of 101 yr) represented 39% more burning per unit time than the maximum of

Table 1. Area burned statistics and calculated fire rotation period for the entire Northern Rockies ecoregion (M333D) and for subalpine forest area within the ecoregion over multiple time intervals since 1900 CE. Note that the two data sources cover different time periods and recording areas. The Northern Rockies Fire Atlas (NRFA) covers federally-managed lands over 1900–2008. The Monitoring Trends in Burn Severity (MTBS) program covers all land area in the region over 1984–2021. MTBS fire perimeters were clipped to the recording area of the NRFA for the FRP calculation combining the two datasets.

	Ecoregion			Subalpine forest			
Time period (CE)	Total area (ha)	Total area burned (ha)	FRP (yr)	Subalpine forest area (ha)	Subalpine area burned (ha)	FRP (yr)	Data source
1900–2021	2 104 292	1 101 180	233	530 975	300 879	215	NRFA + MTBS
1910		512 293	NA		167 075	NA	NRFA
1900–1942		898 317	101		235 818	97	NRFA
1943–1984		36 392	2428		14 284	1561	NRFA
1985–2021	3 317 177	220 537	557	601 739	56 545	394	MTBS
2000–2021		208 218	350		55 972	237	MTBS
2010–2021		130 820	304		33 837	213	MTBS

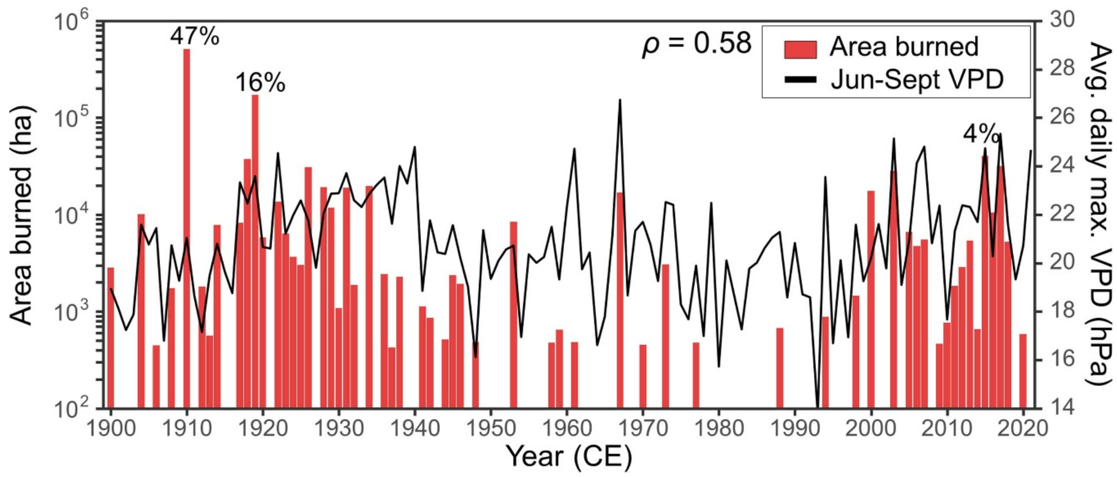

Figure 2. Modern fire history in the northern Rocky Mountain ecoregion (M333D) over 1900–2021. Ecoregion-wide annual area burned (red bars) for 1900–2008 is derived from the NRFA [38], while area burned for 2009–2021 is from MTBS [39]. Summer average daily maximum vapor pressure deficit (VPD, black line; PRISM), spatially averaged over the ecoregion, is correlated with annual area burned ($\rho = 0.58$).

the Southern Rockies, and it occurred at a time when burning in the Southern Rockies was low (figure 5). Maximum historical burning in the Southern Rockies coincided with the early MCA.

Temporal patterns in charcoal influx were more similar between the two regions, but notably, the composite records were standardized, such that overall rates of charcoal influx cannot be compared directly. In both regions, CHAR values were higher on average c. 1500–1000 yr BP and generally lower after c. 800 yr BP (figure 5).

4. Discussion

4.1. Historical, contemporary, and future fire activity in the Northern Rockies

Our network of fire history reconstructions reveals that the Northern Rockies landscape burned with an average paleo-estimated FRP of 164 yr over the past 2500 yr, at rates often exceeding those experienced over the 20th and early 21st centuries. Our study landscape also burned c. 45% more frequently on average than subalpine forests of the southern Rocky Mountains (c. 1000 km south), broadly consistent with previous tree-ring and lake-sediment fire-history records. In the Northern Rockies, several studies in northern Idaho and western Montana provide mean FRI estimates in the range of c. 140–250 yr over recent centuries to millennia [59–63], modestly shorter than Southern Rockies estimates of c. 180–350 yr in southern Wyoming and northern Colorado [15, 49, 64–66]. Spatial variation in fire regimes likely stems from differences in seasonality. While the Southern Rockies receive less total annual precipitation (figure 1), a lack of consistent drought during summer months, in part due to monsoon-like precipitation, likely reduces fuel drying and limits fire activity (figure S8).

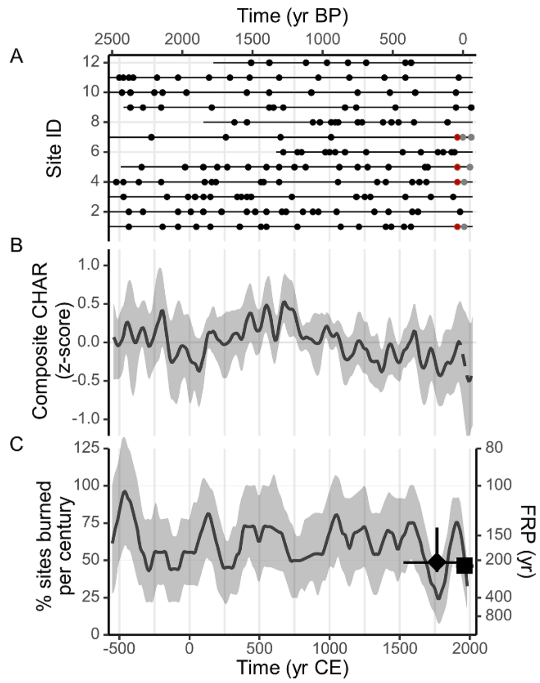

Figure 3. Fire history in the Northern Rockies study area over the past 2500 yr. (A): Fire timing (circles) and record length (horizontal line) for each site, organized from north to south (table S1). Four records had recent charcoal peaks (grey dots) that were shifted to 1910 CE (red dots) in the composite analysis to be consistent with the NRFA (see methods). (B): Composite charcoal accumulation record, smoothed over 100 yr (median ± 90% CI). The line is dashed after 1900 CE to note uncertainty associated with unconsolidated surface sediments. (C): Percentage of sites burned per century (left axis) and fire rotation period (right axis), smoothed over 100 yr (median ± 90% CI). Tree-ring estimated fire rotation periods (diamond) [59] and the 20th-21st-century fire rotation period (square) are shown for comparison. Uncertainty in the 20th-21st century FRP value is encompassed by the size of the symbol, based on ±10% values for total area burned [70]. The *x*-axis scale provides time in years CE (bottom) and calibrated years before present (top, yr BP, where present is 1950 CE).

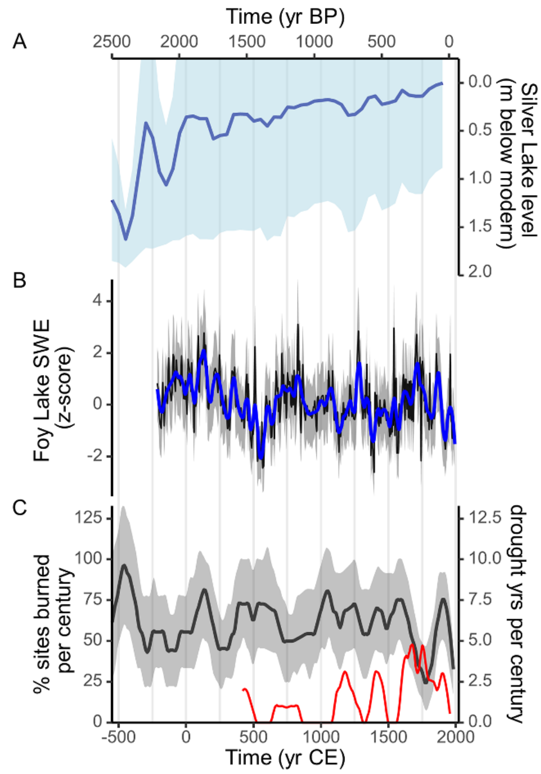

Figure 4. Paleoclimate and fire history in the Northern Rockies region. (A): lake-level reconstruction from Silver Lake, MT, replotted from [54]. (B): reconstructed April 1 snow water equivalent (SWE) from Foy Lake, MT represented as *z*-scores (black), with 95% prediction intervals (grey bands), and smoothed over 100 yr (blue) [55]. (C): percentage of sites burned per century with 90% confidence bands (grey, left axis), and the number of years per century with extreme drought (reconstructed Jun-Aug PDSI < -4) in the study area, smoothed over 100 yr (red, right axis) [53].

Our findings support an overarching influence of climate on fire activity in Northern Rockies subalpine forests. Rates of burning were negatively correlated with average spring snowpack over centennial timescales, consistent with contemporary relationships between annual area burned and the timing of spring snowmelt, which directly affects fire-season length and summer fuel moisture [7, 67] (figure 4). Given strong fire-climate relationships revealed from contemporary, tree-ring, and lake-sediment records spanning decades to millennia [28, 30–32], future warming and drying will likely enable increased fire activity in these forests [4, 5, 68].

Contemporary fire activity in the Northern Rockies so far remains within the HRV (figure 3). Thus, extensive burning during the early 20th century—including the record-setting 1910 fires—does not appear unprecedented within the longer context of recent millennia. Rather, it is the lack of fire during the mid-20th century that differs from the past, likely due to the combination of active fire suppression and less fire-conducive climate (table 1, figure 2) [31, 32]. These results are likely robust to uncertainty inherent in contemporary and palaeoecological estimates of past fire activity. Combining a network of lake-sediment records, each of which records fires within a small area on the landscape, allows us to estimate an area-based fire-regime metric based on the % sites burned per century [25]. This assumes that our sites are representative of the larger landscape and that the burned area represented by each charcoal peak is, on average, similar across records. It also includes some imprecision; for example, multiple fires occurring at a site within a period less than the native resolution of the sediment record are indistinguishable [19]. Documentary and satellite-based fire records also include some imprecision [69]. Indeed, c. 20% of the area within MTBS perimeters is unburned on average [70], thus somewhat overestimating fire activity. The omission of unburned area from the contemporary FRP calculation would accentuate the difference between our modern and paleo estimates, such that contemporary burning would be below the HRV (longer FRP; figure 6). This contrasts with the Southern Rockies,

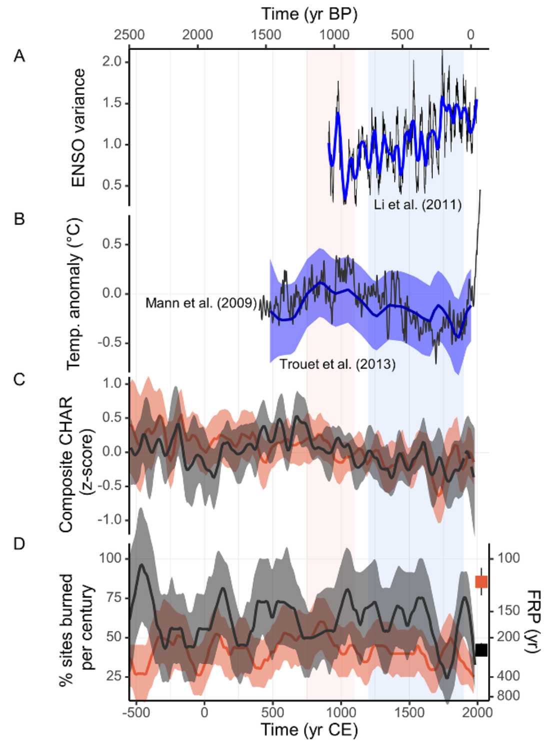

Figure 5. Paleoclimate context and fire history in the Northern Rockies (grey) and Southern Rockies (orange) study areas. (A): Decadal-scale (21 yr) running biweight variance of tree-ring reconstructed ENSO index (unitless, black line), smoothed over 100 yr (blue) [52]. (B): Muliproxy Northern Hemisphere temperature reconstruction represented as anomalies relative to the 20th-century mean (black) [50], and a pollen-based North America temperature reconstruction with ±2 standard error confidence bands (blue) [51]. (C), (D): Composite charcoal accumulation (C) and percent sites burned (D), smoothed over 100 yr with 90% confidence bands. The 21st-century FRP estimate for each region is shown using squares (Northern Rockies = black, Southern Rockies = orange). Uncertainty in fire perimeter mapping from MTBS is approximated by error bars representing FRP calculations with ±10% total area burned for the 21st-century [70].

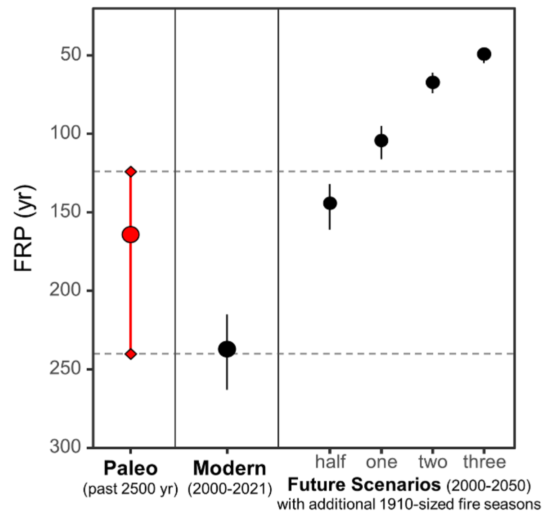

Figure 6. Paleo, modern, and hypothetical future fire rotation periods in subalpine forests in the Northern Rockies study area. The paleo FRP is the average (circle) and central 90% (vertical bars) over the past 2500 yr in the Northern Rockies study area based on the % sites burned per century. Modern FRP is the 21st-century (2000–2021) estimate for subalpine forest in the study area, based on fire perimeters from MTBS. Future scenarios are based on continued fire activity at the 21st-century average rate of burning over the next three decades, with the addition of burning equal to 1/2, one, two, or three years akin to 1910 in the study area (i.e. 167 075 ha burned). Potential imprecision in fire perimeter mapping from MTBS is approximated by error bars representing ±10% total area burned for modern and future FRP estimates [70].

where the 21st-century rate of burning has already exceeded the HRV of recent millennia [26].

Our millennial-scale perspective on fire activity in Northern Rockies subalpine forests helps anticipate if and when contemporary fire activity may exceed the HRV. A modest increase in fire activity above 2000–2021 levels would be consistent with historical rates of burning in the Northern Rockies. However, exceptional fire years like 1910 in the Northern Rockies and 2020 in the Southern Rockies strongly influence fire-regime metrics. One or more years with 1910-level burning within the next three decades in subalpine forests in the Northern Rockies study area would shorten the 21st-century FRP to 96 yr, surpassing the HRV (figure 6). Extensive fire seasons, like 1910, will become progressively more likely as the frequency of climatic extremes increases [58, 71–73]. Thus, as in the Southern Rockies, years with extensive burning in upcoming decades in the Northern Rockies could signal a shift in the fire regime; unlike the past, these years are less likely to be followed by decades of minimal burning [e.g. 68].

The ecological consequences of changing fire regimes depend strongly on whether future fire activity surpasses the longstanding HRV. Species composition in Northern Rockies subalpine forests has remained relatively stable over the past several millennia [62, 74], when fire activity was similar to or greater than that of the 21st century (figure 3). Additionally, although the combination of warming and drying and higher fire activity can limit recruitment of subalpine species [75–78], future climate is projected to remain suitable for tree regeneration in the Northern Rockies through at least mid-century [79]. Therefore, Northern Rockies subalpine forests could remain resilient to modest increases in burning in the near term; increases in fire activity that move the system outside of the HRV, however, have the potential to initiate large-scale ecological transformations, particularly in the context of overall climate warming [80, 81].

4.2. Asynchronous burning in the Northern and Southern Rockies over the past 2500 yr

Our results provide little evidence of synchronous variations in fire activity across the Northern and Southern Rockies in response to late-Holocene climatic variations. Contrary to expectation, Northern Rockies fire activity did not increase during the

Medieval Climate Anomaly (MCA, c. 1200–800 yr BP), when Northern Hemisphere temperatures were ~0.3 °C above the average of the cooler Little Ice Age (LIA, c. 750–50 yr BP) [50, 51, 56], and when burning was widespread in the Southern Rockies and more broadly across the West [16, 25]. The lack of maximal burning during the MCA in the Northern Rockies may reflect a more subdued climate anomaly in the region. There is little evidence of anomalous MCA warmth in the Northern Rockies in terms of summer temperatures (figure S7) [56], highlighting that broad-scale temperature reconstructions may not reflect regional patterns. It is also possible that the effects of strong and persistent La Niña-like conditions in the tropical Pacific during the MCA [50, 51] overrode the influence of any temperature changes in the Northern Rockies. La Niña conditions are associated with above-average winter and spring precipitation in the northwestern U.S., and warm, dry climate conditions and above-average fire activity in the southwest and the Southern Rockies [82]. Given these regional differences in the effects of ENSO variation, it is not surprising that fire activity responded differently in the two regions during the MCA. How future climate impacts will interact with ENSO variation to influence fire activity in each region remains uncertain, with important implications for ecological processes, including forest demography [83]. Future research combining multiple landscape-scale fire histories from across the Rockies will help resolve regional fire-regime variation and responses to climate drivers.

4.3. Summary and conclusions

This study provides quantitative estimates of past variation in fire activity in Northern Rockies subalpine forests, and it highlights strong climatic controls of fire activity across the region. Our results reveal that 21st-century burning in the Northern Rockies remains within the HRV of the past 2500 yr; however, as the frequency of years with high fuel aridity and associated burning increases under future climate in the Northern Rockies, fire activity will likely surpass that experienced in the past. More broadly across the West, our results imply that the emergence of fire-regime shifts will be marked by exceptional fire years in individual landscapes and regions, as seen in the Southern Rockies, which may result in a 'ratchet of events' driving ecosystem changes across space and time [84, 85]. Furthermore, while climate-enabled extreme fire events may have historical precedents, wildfire risk from unintentional ignitions—as well as exposure of communities in the wildland-urban interface—far exceed historical conditions [13]. Planning for community response and resource management would benefit from increasingly anticipating extreme events and the risks they pose to human health, infrastructure, and ecosystem services at regional scales.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5061/dryad.3n5tb2rnv [86]. Data will be available from 15 September 2023.

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