Rocky Mountain subalpine forests now burning more than any time in recent millennia

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Edited by Michael E. Mann, Pennsylvania State University, University Park, PA, and approved April 28, 2021 (received for review February 24, 2021)

The 2020 fire season punctuated a decades-long trend of increased fire activity across the western United States, nearly doubling the total area burned in the central Rocky Mountains since 1984. Understanding the causes and implications of such extreme fire seasons, particularly in subalpine forests that have historically burned infrequently, requires a long-term perspective not afforded by observational records. We place 21st century fire activity in subalpine forests in the context of climate and fire history spanning the past 2,000 y using a unique network of 20 paleofire records. Largely because of extensive burning in 2020, the 21st century fire rotation period is now 117 y, reflecting nearly double the average rate of burning over the past 2,000 y. More strikingly, contemporary rates of burning are now 22% higher than the maximum rate reconstructed over the past two millennia, during the early Medieval Climate Anomaly (MCA) (770 to 870 Common Era), when Northern Hemisphere temperatures were ∼0.3 °C above the 20th century average. The 2020 fire season thus exemplifies how extreme events are demarcating newly emerging fire regimes as climate warms. With 21st century temperatures now surpassing those during the MCA, fire activity in Rocky Mountain subalpine forests is exceeding the range of variability that shaped these ecosystems for millennia.

climate change | fire ecology | wildfires | extreme events | paleoecology

The 2020 fire season punctuated a trend of increasing wildfire activity throughout the 21st century across the western United States ("the West"). This trend is well-linked to increasingly fire-conducive climate conditions (1) and anthropogenic climate change (2), and it is coming with devastating human impacts (3).

Across different ecosystems and regions of the West, the causes of increasing fire activity vary (4–6), and thus so too do potential management and policy solutions (7, 8). Over a century of policies have limited Indigenous fire stewardship and emphasized fire suppression, leading to significant fire deficits in low- and mid-elevation forests that historically burned frequently in low-intensity surface fires (9, 10). This differs from high-elevation subalpine forests, where fire history records show that large, stand-replacing fires typically burned once every one to several centuries over recent millennia (11–17). Continued 21st century warming in these high-elevation forests is predicted to increase fire activity beyond the historical range of variability (18, 19). Detecting if and when such changes emerge, however, and understanding the magnitude of ongoing change requires placing contemporary burning in the context of the past.

Here, we use a unique network of paleofire records spanning the past 2,000 y to test the hypothesis that 21st century climate change has led to unprecedented fire activity in Rocky Mountain subalpine forests. These high-elevation forests are useful sentinels of climate change impacts because their typically cool, moist climate limits frequent fire, and they have historically experienced less land-use change and fire suppression than lower-elevation forests. To place late 20th and 21st century wildfire activity in a millennial-scale context, we draw on existing tree-ring and lake sediment records of fire history from subalpine forests in a ∼30,000 km^2 region in the central Rocky Mountains of Colorado and Wyoming (Fig. 1*A*), similar in size to the Greater Yellowstone Ecosystem.

Results and Discussion

Area burned across all ecosystems in the central Rocky Mountains increased significantly since 1984 ($\rho = 0.40$, $P = 0.015$), a trend strongly correlated with average May to September vapor pressure deficit (VPD; $\rho = 0.75$, $P < 0.001$; Fig. 1*B*). VPD reflects atmospheric demand for water and is well-linked to increased fire activity because of its influence on fuel aridity (1, 2, 6). The vast extent (95%) of burning since 1984 occurred in the 21st century, with 2020 alone accounting for 44% of area burned over this period (Fig. 1*B* and Table 1). Within the subalpine forests of our focal study area, defined by the dense network of fire history records (inset box, Fig. 1*A*), the 2020 wildfires were even more pronounced, accounting for 72% of the total area burned since 1984 (Table 1 and *SI Appendix*, Fig. S1).

While the majority of area burned in subalpine forests typically occurs in years with extreme seasonal climate conditions (20, 21)—such as the 1988 Yellowstone Fires and the 2020 fires in our study area—such conditions are occurring more frequently in the 21st century (Fig. 1*B* and *SI Appendix*, Fig. S1). In our focal study area, just 5 y account for 99% of the total area burned since 1984, with shortening gaps between extreme years: 2002, 2012, 2016, 2018, and 2020 (*SI Appendix*, Fig. S1). This trend foreshadows continuing increases in wildfire activity and extreme fire seasons with higher aridity in coming decades (22), as projected across Rocky Mountain forests (18, 19).

Significance

Climate change is increasing wildfire activity across the western United States, with unprecedented rates of burning expected in many western forests by mid-century. Here, we use a unique network of fire history records to show that after the extreme 2020 fire season, Rocky Mountain subalpine forests are now burning more than at any point in the past 2,000 y, exceeding variability experienced in response to past climate extremes. Increasingly warm, dry conditions in the 21st century are enabling the exceptional rates of burning, including 2020, consistent with long-standing links between climate and fire in subalpine forests. Continued warming will reinforce newly emerging fire regimes, with significant implications for ecosystems and society.

Author contributions: P.E.H. and B.N.S. designed research; P.E.H., B.N.S., and K.D.W. performed research; P.E.H. and K.D.W. analyzed data; and P.E.H., B.N.S., and K.D.W. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2103135118/-/DCSupplemental.

Published June 14, 2021.

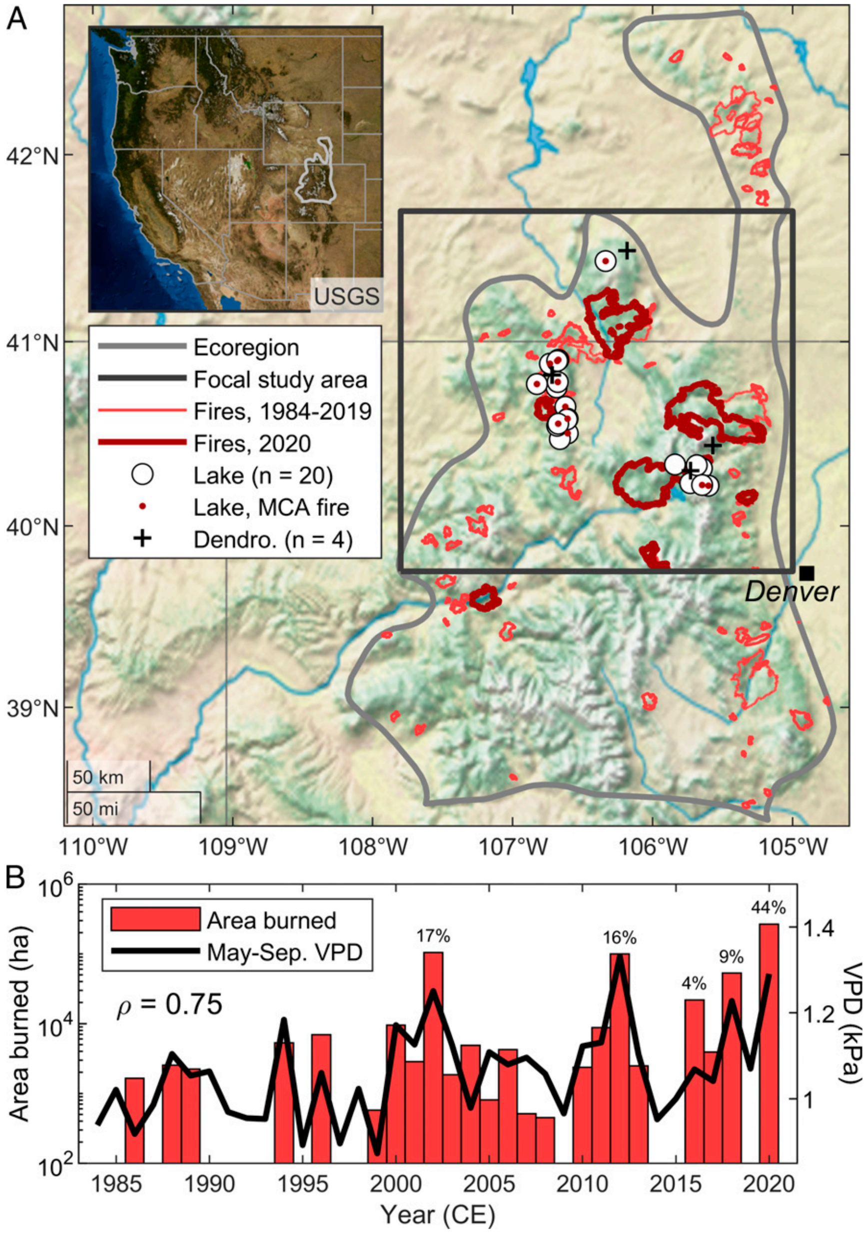

Fig. 1. Wildfire and climate in the central Rocky Mountains. (*A*) Central Rocky Mountains ("Ecoregion") and focal study area, with fire perimeters from 1984 to 2019 (thin, light red lines) and 2020 (thick, dark red lines; see also *SI Appendix*, Fig. S3). The 20 lakes with published paleofire records are shown with white circles; lakes recording fire events during the early MCA, c. 770 to 870 CE, are shown in red. The general locations of published tree-ring–based stand-age and fire-scar records used to reconstruct fire extent are shown with black plus symbols; the geographic extent represented by each study exceeds the extent of the symbols. (*B*) Ecoregion-wide area burned for fire perimeters displayed in *A* and average May to September VPD. Percentages above red bars are the proportion of total area burned (from 1984 to 2020) contributed by the given year.

The extensive fire activity during the 21st century is unprecedented in the past two millennia in our focal study area (Fig. 2). To directly compare recent burning to paleofire records, we summarized contemporary fire activity using fire rotation periods (FRPs), defined as the time required to burn an area equal in size to the area of interest, which in this case is the total area of subalpine forests in our focal study area. By sampling across this large area, we substitute space for time to characterize contemporary FRPs. During the 21st century (2000 to 2020), the FRP in our focal study area was 117 y. The FRP from 1984 to 2020, incorporating the last 16 y of the 20th century with little fire activity, was 204 y (Table 1), within the historical range of variability defined by tree-ring and lake sediment records (Fig. 2*C*). Integrating published tree-ring–reconstructed FRPs from eight subregions in our focal study area (11, 15, 17, 23), the median FRP (95% CI) was 261 y (183 to 398) from c. 1630 to 1860 CE (Common Era) and 315 y (295 to 1,520) from c. 1861 to the mid-20th century CE (Fig. 2*C* and *SI Appendix*, Fig. S2); the FRPs from these periods are not significantly different (Wilcoxon rank sum statistic = 55, $P = 0.195$). Similarly, in the subalpine forest watersheds where lake sediments record fire history over the past two millennia, 44% experienced a fire event within any given century on average, analogous to an FRP of 230 y (Fig. 2 *A* and *C*). Therefore, the 21st century FRP of 117 y, largely because of the 2020 fire season, represents nearly a doubling of the average rate of burning over the past 2,000 y.

Table 1. Contemporary area burned statistics and fire rotation period (FRP) calculations for the focal study area for different time periods from 1984 to 2020

	Entire study region (7,817,464 ha)	Subalpine forest in focal study area (1,395,870 ha)	
Time period (CE)	Area burned (ha) (% of total)	Area burned (ha) (% of total)	FRP (y)
1984 to 2019	340,216 (56%)	71,953 (28%)	698
1984 to 2020	606,263 (100%)	252,811 (100%)	204
2000 to 2019	320,939 (53%)	70,175 (28%)	398
2000 to 2020	586,985 (97%)	251,033 (99%)	117
2010 to 2020	457,340 (75%)	227,356 (90%)	68
2020	266,046 (44%)	180,858 (72%)	–

The 21st century FRP also exceeds the maximum rate of burning reconstructed over the past 2,000 y. Modest warming during the early Medieval Climate Anomaly (MCA, 770 to 870 CE) coincided with the maximum of 67% of sites recording fire events within a century, corresponding to an FRP of 150 y (Fig. 2*C*). The 21st century FRP of 117 y represents 22% more burning per century than the early MCA maximum (Fig. 2*C*). Fire activity over the past two millennia also broadly tracked paleotemperatures across North America (24) and the Northern Hemisphere (25) (Fig. 2 *B* and *C*), consistent with links between climate and fire seen in the contemporary record (Fig. 1*B* and *SI Appendix*, Fig. S1). Although we cannot directly compare area-burned statistics from the paleofire records to the size of contemporary wildfires, burning during the early MCA was concentrated within a subset of sites (sites 2 to 13 in Fig. 2*A*) spanning an area similar in size to the extent of the major 2020 wildfires (Fig. 1*A* and *SI Appendix*, Fig. S3).

Subalpine forest fire regimes are unlikely to return to the late-Holocene range of variability in this century (Fig. 2*C* and *SI Appendix*, Fig. S2*C*). It would take two decades with no additional burning following 2020 to return the 21st century FRP (i.e., 2000 to 2040) in our focal study area to the late-Holocene average of 230 y. Even returning to the 1984 to 2020 rate of burning for the next three decades would keep the 21st century FRP near the late-Holocene limit of 150 y (Fig. 2*C* and *SI Appendix*, Fig. S2*C*). The 2020 fire season thus marks the emergence of 21st century fire regimes with distinctly higher rates of burning not just from the late 20th century but relative to the past two millennia.

The primary importance of climate in enabling widespread burning, in the past and present, does not mean that nonclimatic factors are unimportant for fire activity at smaller scales. Extreme winds over hourly and daily time scales drove extraordinary growth of individual fires in 2020, with Colorado's East Troublesome Fire crossing the fuel-barren Continental Divide. The 2020 fires also burned forests with extensive insect-caused tree morality, and while this likely altered stand-level fire behavior (26), it does not explain the West-wide pattern of increased burning in recent decades (27). Furthermore, while fire suppression and prior land uses have altered fire regimes in lower-elevation forests, long fire-free intervals (Fig. 2*A*) and less intensive forest management minimize these impacts in subalpine forests. Instead, the increasing magnitude and frequency of extreme moisture deficits in the 21st century (Fig. 1*B*), rather than increased fuel abundance, lacks precedent in recent millennia and has driven the 21st century shift in fire activity.

The combination of increased burning (18, 19) and more stressful postfire climate conditions for tree regeneration (28) in upcoming decades foreshadows the potential for widespread loss of subalpine forest resilience to wildfire (29). The extensive burning during the early MCA, for example, transformed some closed-canopy forests near the tree line into lower-density ribbon forests, a structure that persists today (30). Additionally, extensive burning during the MCA reduced the landscape connectivity of late-successional forests, likely explaining why elevated burning was not sustained even as warming continued for several centuries (Fig. 2*C*) (12). Such decreased forest density or connectivity could eventually create a negative feedback with fire activity (18, 29), but this is unlikely in upcoming decades. Even at the 2010 to 2020 rate of burning, it would take six decades to burn an area equal to all subalpine forests in the focal study area. Area burned will likely continue to increase before fuel limitations, other ecosystem changes, or long gaps between extreme fire years reduce subalpine forest burning to late-Holocene levels.

Rates of burning now nearly twice the late-Holocene average and exceeding the maxima of the MCA underscore the high sensitivity of regional fire regimes to climate change. From the paleoecological perspective, unprecedented burning in the 21st century is not surprising, given that Northern Hemisphere temperatures have now risen ~0.5 °C above the MCA maximum (Fig. 2*B*). Our findings are also consistent with the predicted development of novel fire regimes across the Rocky Mountains by the early to mid-21st century (18, 19). The emergence of unprecedented burning by 2020 suggests that the central Rocky Mountains are following a trajectory consistent with the warmer and drier climate scenarios used in projections of future fire activity. Only by returning to the 1984 to 2020 average rate of burning would 21st century fire regimes in our focal study area realign with the highest rates of burning over the past 2,000 y, an unlikely scenario under even the most modest climate change projections (18, 19).

As the 21st century rate of burning moves beyond the range of late-Holocene variability, planning across all scales—from individuals to utility companies, municipalities to the federal government—can no longer be reasonably based on expectations from the past. The 2020 fire season serves as an example of how increasingly fire-conducive climate conditions have made Rocky Mountain subalpine forests more flammable now than at any point in recent decades or millennia, a trend expected to continue with climate warming.

Materials and Methods

We characterized contemporary fire activity and climate in the central Rocky Mountains within Bailey's M331H and M331I ecosections (Fig. 1*A*). Fire perimeters were obtained from the Monitoring Trends in Burn Severity program (MTBS, https://www.mtbs.gov/) for wildfires from 1984 to 2018 (as 2019 fires were not yet available) and from the National Interagency Fire Center (NIFC, https://data-nifc.opendata.arcgis.com/) for wildfires from 2019 and 2020. To be consistent with the fire-size cut off in the MTBS dataset, we only used fires >405 ha (1,000 acres) from 2019 and 2020. Annual average May to September VPD for the study region was obtained from gridMET (31) (http://www.climatologylab.org/gridmet.html). We used Spearman rank correlation to assess trends in area burned and VPD and to compare these two time series.

To explicitly compare contemporary burning to fire activity reconstructed over the past 2,000 y, we further defined a focal study area, reflecting subalpine forests represented by the network of paleofire records. The focal study area was defined as the area of subalpine vegetation, within the ecosections noted above, within the area from 39.75 to 41.70° N latitude and 105.0 to 107.8° W longitude (Fig. 1*A*). Subalpine vegetation classes were

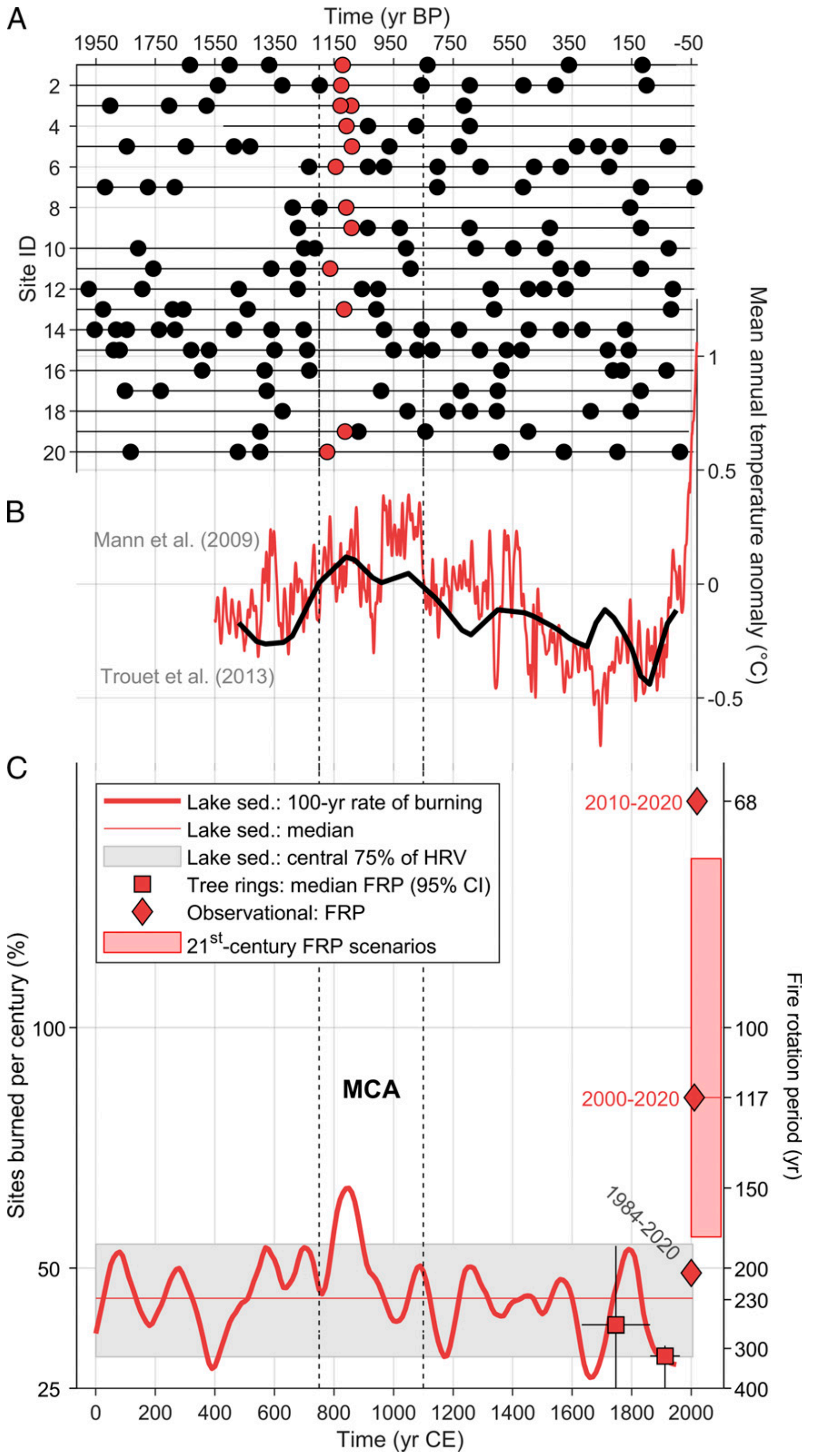

Fig. 2. Subalpine forest fire history. (*A*) Fire events (circles) from the 20 sites in Fig. 1*A*, ordered from north to south (1–20). Black horizontal lines indicate when lakes were recording; red circles highlight the century with maximum burning. (*B*) Northern Hemisphere (red, 10 y) and North America (black, 30 y) mean annual temperature reconstructions, with the MCA highlighted by dashed vertical lines; Mann et al. (25) data extended from 2006 with data from the Climate Research Unit. (*C*) Paleofire history from lake sediments (percent sites burned per century, left axis, and paleo FRP, right axis) from *A*, with median (red line) and the central 75% of the historical range of variability (HRV, gray rectangle); median tree-ring–derived FRP for c. 1611 to 1863 and 1864 to 1944 CE (red squares), calculated from eight FRP values (11, 15, 17, 23) with 95% bootstrapped CI; contemporary FRP values for subalpine forests within the focal study area (red diamonds); and 21st century FRP scenarios, assuming continued rates of burning between the 1984 and 2020 rate (FRP of 204 y) and the 2010 to 2020 rate (FRP of 68 y; see also *SI Appendix*, Fig. S2).

derived from LANDFIRE's Environmental Site Potential product (https://landfire.gov/; *SI Appendix*, Fig. S3). In defining the spatial extent of our focal study area, we balanced the need to capture enough area to characterize fire regimes over recent decades while still reflecting the forest types represented by the network of paleofire records. We used the FRP to characterize the rate of contemporary subalpine forest burning, defined as the amount of time it takes to burn an area equal in size to our focal study area: time period considered/(total area burned/size of study area).

To characterize fire history over the past several centuries in subalpine forests from within the focal study area, we utilized four published tree-ring reconstructions of past fire extent. Each study provides FRP estimates for varying study areas, eight in total: six in Rocky Mountain National Park (11, 17), one in the Park Range in northern Colorado (23), and one in the Medicine Bow Mountains in southern Wyoming (15) (Fig. 1*A* and *SI Appendix*, Fig. S3). Fire extent was reconstructed using dendrochronology to date forest age classes and identify precise fire years with fire scars. Three of the four studies (11, 15, 23) estimated FRPs for two distinct time periods, generally c. 1600s through the mid-1800s and from the mid-1800s through the early to mid-1900s. We calculated FRP statistics for the fourth study to approximate these time periods based on data presented in *SI Appendix*, Table S4 in Sibold et al. (21) (i.e., for 1654 to 1863 and 1864 to 2000). The precise cutoff dates among studies varied based on the oldest fires confidently reconstructed and the timing of fires in the 1800s. To generate a pooled estimate of the FRP representing the focal study area, we calculated the median FRP from among the eight FRP estimates within two time periods: c. 1650 to 1870 and 1870 to 2000. We estimated the 95% CIs around the median FRP from 1,000 bootstrapped samples.

We characterized fire history over the past 2,000 y using a network of 20 published fire reconstructions based on distinct peaks in macroscopic charcoal in high-resolution lake sediment records (12–14, 16, 32, 33). All records come from small (<10 ha) lakes surrounded by subalpine forests dominated by lodgepole pine (*Pinus contorta* var. *latifolia*) at lower elevations and Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) at higher elevations. Chronologies were based on ^{210}Pb and ^{14}C dates, and macroscopic charcoal (>150 μm) was sampled contiguously, yielding an average c. 5 to 20 y/sample in each record. Distinct charcoal peaks were identified using the CharAnalysis program and interpreted as fire events, representing one or more fires within ∼1 to 3 km of the lake within the sample interval. We used the fire history reconstructions presented in the original publications, 19 of which were developed by the authors of the current study.

We summarized regional paleofire activity from the lake sediment records by calculating the percent of sites with fire events within overlapping 100-y periods and smoothed this time series using locally weighted regression with a 10-y window. To compare fire activity across our paleofire network to FRP statistics from tree-ring and contemporary records, we calculated a paleo-FRP following Calder et al. (12) defined as the amount of time it takes to record a total number of fire events equal to the number of sites recording. At the 100-y time intervals used to calculate the percent of sites burned, the paleo FRP is defined as the following: 100 y/% sites burned.

Data Availability. Data and code used here are available via the Dryad Digital Repository [(34); DOI: 10.5061/dryad.rfj6q579n]. Most datasets are all also publicly available through the links in *Materials and Methods* (i.e., MTBS, NIFC, GridMET, and LANDFIRE) or repositories associated with the original publications [i.e., https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/fire-history for Calder et al. (12), https://doi.org/10.5061/dryad.q2b8t for Higuera et al. (14), and https://doi.org/10.6084/m9.figshare.988687.v19 for Dunnette et al. (13)].

ACKNOWLEDGMENTS. We thank T. Hudiburg, K. McLauchlan, and S. Dobrowski for comments. This work was funded by NSF Grants DEB-1655121 and OISE-0966472 to P.E.H. and DEB-1655189 and BCS-0845129 to B.N.S. We thank the numerous people involved in field and laboratory work associated with the original publications utilized here and the federal agencies granting research permits to perform this work.

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Supplementary Information for

Rocky Mountain subalpine forests now burning more than any time in recent millennia

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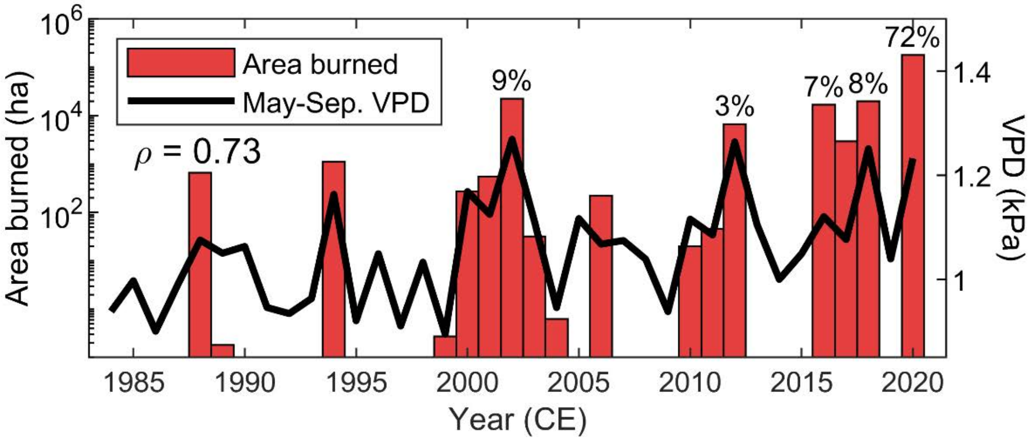

Figure S1. Wildfire and climate in the focal study area. Subalpine forest area burned within the focal study area (defined in Fig. 1A), and average May-September vapor pressure deficit (VPD) from Grand Lake, Colorado. Percentages above red bars are the proportion of total area burned (from 1984-2020) contributed by the given year. The area burned and VPD time series have a Spearman rank correlation (ρ) of 0.73 ($p < 0.001$).

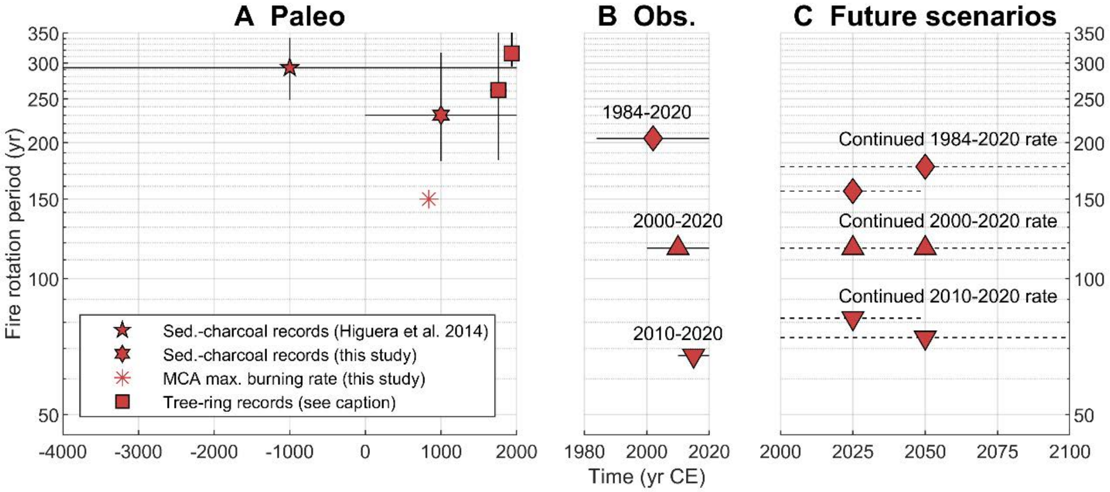

Figure S2. Historical and contemporary fire rotation periods, and hypothetical future scenarios for subalpine forests in the focal study area. (A) Fire rotation periods (FRPs) from sediment-charcoal and tree-ring records from subalpine forest watersheds within the focal study area. Sediment-charcoal records are the mean and bootstrapped 95% confidence interval (1) or the central 75% of all 100-yr estimates (as in Fig. 2C, this study). Tree-ring-based reconstructions (2-5) are the median and the bootstrapped 95% confidence interval from published FRPs or fire extent statistics from eight watersheds (as in Fig. 2C; see Materials and Methods). (B) Contemporary observations are from 1984-2020, 2000-2020, and 2010-2020. (C) Future scenarios for 2000-2050 and 2000-2100 use the observed area burned from 2000-2020, and then assume a continued rate of burning equivalent to the three time periods in (B). For all panels, horizontal lines reflect the time period covered by each FRP statistic.

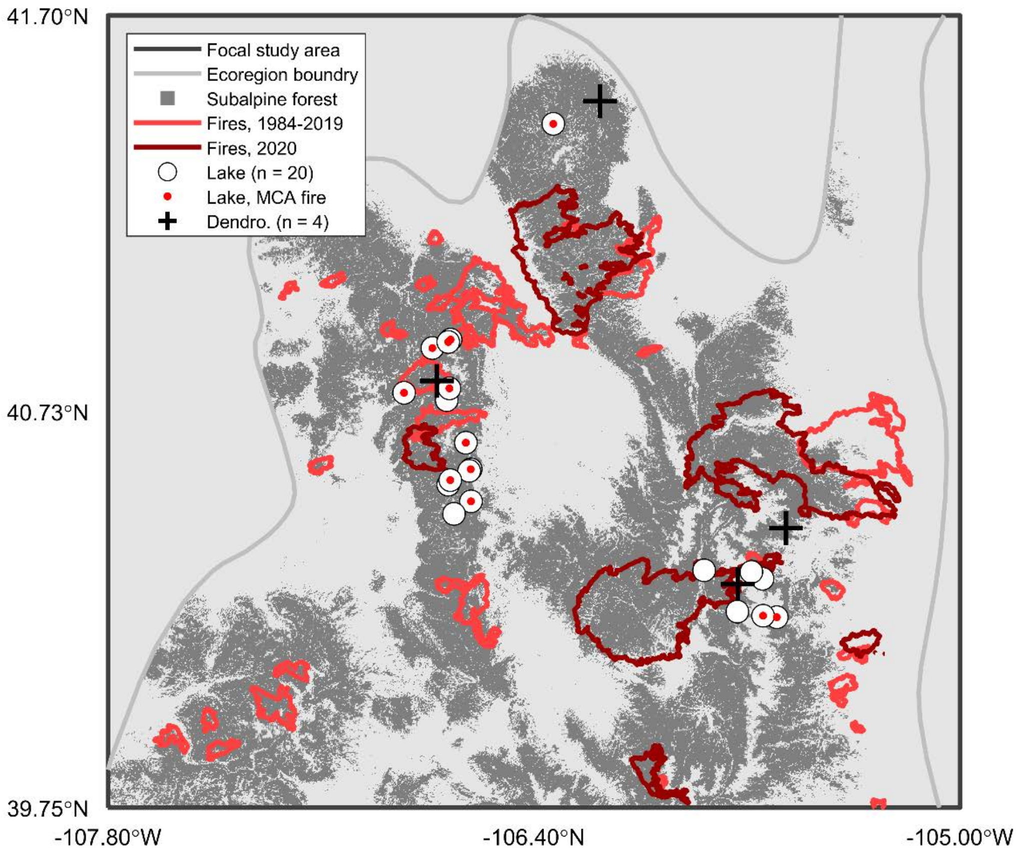

Figure S3. Subalpine forest vegetation within the focal study area. Focal study area (map extent), as in Figure 1A, with subalpine forest, as defined by the LANDFIRE environmental site potential (ESP) product. LANDFIRE ESP is a 30-m resolution product representing the vegetation that could occupy a site based on the biophysical setting (www.landfire.gov). Subalpine forest vegetation was defined by combining the following ESP classes, within the broader vegetation classifications of upland forest, upland woodland, and wetland forest: Rocky Mountain Dry-Mesic Spruce-Fir Forest and Woodland; Rocky Mountain Mesic-Wet Spruce-Fir Forest and Woodland; Rocky Mountain Lodgepole Pine Forest. The 20 lakes with published paleo-fire records are shown with white circles (1, 6-8); lakes recording fire events during the early Medieval Climate Anomaly, c. 770-870 CE, are shown in red. The general locations of published tree-ring-based stand-age and fire-scar records used to reconstruct fire extent and fire rotation periods are shown with white squares (2-5).

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