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A fire deficit persists across diverse North American forests despite recent increases in area burned

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Rapid increases in wildfire area burned across North American forests pose novel challenges for managers and society. Increasing area burned raises questions about whether, and to what degree, contemporary fire regimes (1984–2022) are still departed from historical fire regimes (pre-1880). We use the North American tree-ring fire-scar network (NAFSN), a multi-century record comprising >1800 fire-scar sites spanning diverse forest types, and contemporary fire perimeters to ask whether there is a contemporary fire surplus or fire deficit, and whether recent fire years are unprecedented relative to historical fire regimes. Our results indicate, despite increasing area burned in recent decades, that a widespread fire deficit persists across a range of forest types and recent years with exceptionally high area burned are not unprecedented when considering the multi-century perspective offered by fire-scarred trees. For example, 'record' contemporary fire years such as 2020 burned 6% of NAFSN sites—the historical average—well below the historical maximum of 29% sites that burned in 1748. Although contemporary fire extent is not unprecedented across many North American forests, there is abundant evidence that unprecedented contemporary fire severity is driving forest loss in many ecosystems and adversely impacting human lives, infrastructure, and water supplies.

Wildland fire was common and widespread across many forests and woodlands in North America prior to the late 19th and early 20th centuries. In subsequent decades, fire exclusion—the practice of preventing and suppressing nearly all wildland fires—occurred as the result of the disruption of traditional burning, livestock grazing, and active suppression of human- and lightning-ignited fires[1–4]. As a consequence, average annual area burned since the late 19th and early- to mid-20th centuries is generally less than that experienced under historical fire regimes across many North American forests, resulting in a widespread 20th century 'fire deficit' relative to earlier time periods[5–7]. However, area burned by wildfire has increased across much of North America over the last few decades[8,9]. Over this time period (mid-1980s—present), several regions have experienced individual years with exceptionally high area burned[10–12], leading to questions about whether recent fire years are unprecedented[13]. As area burned has increased rapidly since the mid-1980s in parts of North

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America, is it possible that the fire deficit has been reduced or eliminated? Questions also remain as to whether some individual recent years with extensive fire (e.g., 2016 in the southeastern United States; 2020 in the western United States; 2023 in Canada) begin to approach or exceed the range of variation in area burned prior to widespread fire exclusion[13,14].

There has been long-standing interest in the scientific community if, and to what degree, contemporary fire regimes are departed from historical reference conditions in terms of fire frequency or annual area burned[15–17]. Models of historical fire frequency[18] have been compared with contemporary fire data to quantify fire regime departures, which generally demonstrate that there is a fire deficit in some forest and woodland systems[5,15,19,20]. These models of historical fire frequency, however, lack the annual resolution that is necessary to compare to individual contemporary years. Similarly, fire proxies from charcoal preserved in lake sediments and bogs suggest that there is considerably less area burned in the 20th century compared with previous centuries[7,21], although some localized studies that are primarily relevant to colder forest types suggest that recent fire activity is within the historical range of variability[22,23] or in some cases unprecedented[24]. Although these deep time paleo proxies provide long records of fire activity (up to thousands of years), they generally lack fine spatial and temporal resolution, thereby limiting our ability for comparison with individual years during the contemporary time period (but see [25]) and are generally concentrated in cooler forests with historically infrequent fire regimes.

Tree-ring fire-scar records provide annually resolved, site-specific information on fire occurrence. Collectively, tree-ring fire-scar records across many North American forest types provide convincing evidence that fire activity decreased substantially starting in the late-19th century[26,27], but until recently, inferences about contemporary fire regimes across broader regions and the continent were constrained by the limited spatial extent of individual studies[28]. The recent compilation of >1800 crossdated tree-ring fire-scar records in the North American tree-ring fire-scar network (NAFSN)[29] enables direct comparisons of historical and contemporary fire activity across a broad range of forest types and biophysical climatic gradients. This large geospatial dataset, with many sites recording the presence/absence of fire since 1600, makes it possible to quantify current departures in fire regimes and determine how recent large fire seasons compare to historical fire regimes across a range of forest types. Previous investigations using tree-ring fire-scar networks have been incredibly valuable in understanding broadscale fire, climate, and human patterns. For example, Kitzberger et al[30]. used 238 fire-scar sites to evaluate fire-climate relationships in western North America and Swetnam et al[31]. used >800 sites to disentangle the relationship between fire, climate, and humans in the western US.

Recent rapid increases in area burned pose novel challenges for managers and policy makers seeking to protect homes and infrastructure and manage forests, sensitive wildlife habitat, water supplies, and carbon stocks[10,32–34]. Comparing contemporary fire activity to an historical reference period not influenced by fire exclusion provides important context for management and policy[35], as well as vital information regarding the potential for continued and increasing societal impacts from fire (e.g., threats to life, property, and water supplies, and impacts of smoke and forest loss). For example, the historical range of variability can serve as a useful benchmark for managing resilient landscapes[36,37], acknowledging that this metric may not be the most appropriate target under changing climate and social conditions[38,39]. If recent years with widespread fire are indeed unprecedented, then continued aggressive fire suppression, particularly during windows of extreme fire weather conditions, may be justified to reduce their impacts. Alternatively, if contemporary fire activity does not exceed historical ranges, then managers could (i) focus less on fire size and annual area burned, and more on fire severity (e.g., the proportion of trees killed by fire), which is increasing across some regions in the United States and Canada[9,40], (ii) focus on adaptation and resilience of human and natural communities to fire[41], and/or (iii) expand the area treated by prescribed fires[42,43] or wildfires that occur under more moderate weather conditions, which are better aligned with the behavior and effects of historical fires in many ecosystems.

Our overarching goal was to determine whether contemporary (1984–2022) forest and woodland fire regimes represented by NAFSN are still departed from the historical (1600–1880) levels of burning given increased fire activity in recent decades. To do so, we ask three questions: (1) whether the rate at which NAFSN sites burned prior to 1880 differs from the rate at which NAFSN sites burned from 1984–2022, thereby determining if there is a fire surplus or deficit; (2) whether individual recent fire years are unprecedented relative to historical fire regimes by comparing the annual proportion of sites that burned in each period; and (3) how the proportion of years in which zero sites burned (hereafter 'non-fire years') in the contemporary period compared to the historical prevalence of non-fire years. Historical fires (pre-1880) were characterized using annually resolved tree-ring fire-scar data from NAFSN and contemporary fires (1984–2022) were characterized by intersecting NAFSN sites with detailed annual fire perimeters (Fig. S1). As such, we quantified the number and proportion of sites burned each year in each time period. All analyses were conducted across NAFSN sites in the United States and Canada and by ecoregion (Fig. 1)[44]. We used ecoregions to assess broad differences in fire trends among forest types across our study area, though we acknowledge that there is variability in dominant tree species across the study area and within ecoregions (Fig. S2). Our study provides important context about altered fire regimes by comparing contemporary fire occurrence to a multi-century, pre-fire exclusion reference period across a diverse range of forest types in the United States and Canada. Throughout this paper, we use the term 'traditional burning' to encompass both Indigenous fire stewardship and post-colonization traditions of burning that were widely adopted in the eastern United States[45].

Results

Overall, contemporary fires (1984–2022) burned NAFSN sites less frequently than fires during the historical reference period (pre-1880), indicating that a substantial fire deficit persists and is still accumulating across many forests and woodlands across the United States and Canada (Table 1). Based on the historical fire-scar record, NAFSN sites collectively would be expected to have burned 4346 times from 1984–2022, yet they burned 989 times, or only 23% of what would be expected under the historical fire regime. In all ecoregions except the Taiga & Hudson Plain, NAFSN sites exhibit a statistically significant fire deficit from 1984–2022 (Table 1). A statistically significant fire surplus was observed from 1984–2022 in the Taiga & Hudson Plain ecoregion.

Recent years of particularly widespread fire activity are not unprecedented when compared to the historical reference period across NAFSN sites in the United States and Canada (Fig. 2). The year 2020 had the highest percent of sites recording fire in the contemporary time period, with 6% of NAFSN sites burned. This percentage is far below the 29% burned in the most widespread historical fire year (1748) (Fig. 2a) and equal to the average of 6% that burned per year across NAFSN sites during the historical period (Table 2). To address the varying density of fire-scar sites across the study region, we conducted a parallel analysis summarizing historical and contemporary fire within hexagonal polygons (hereafter 'hexels'; Fig. 1), thereby giving equal weight to each hexel, regardless of how many NAFSN sites they contained. To do so, we calculated the percent of NAFSN sites that burned per year within each hexel, then averaged these values for each year across all hexels ($n = 120$; Fig. 1) and produced frequency distributions for historical and contemporary time

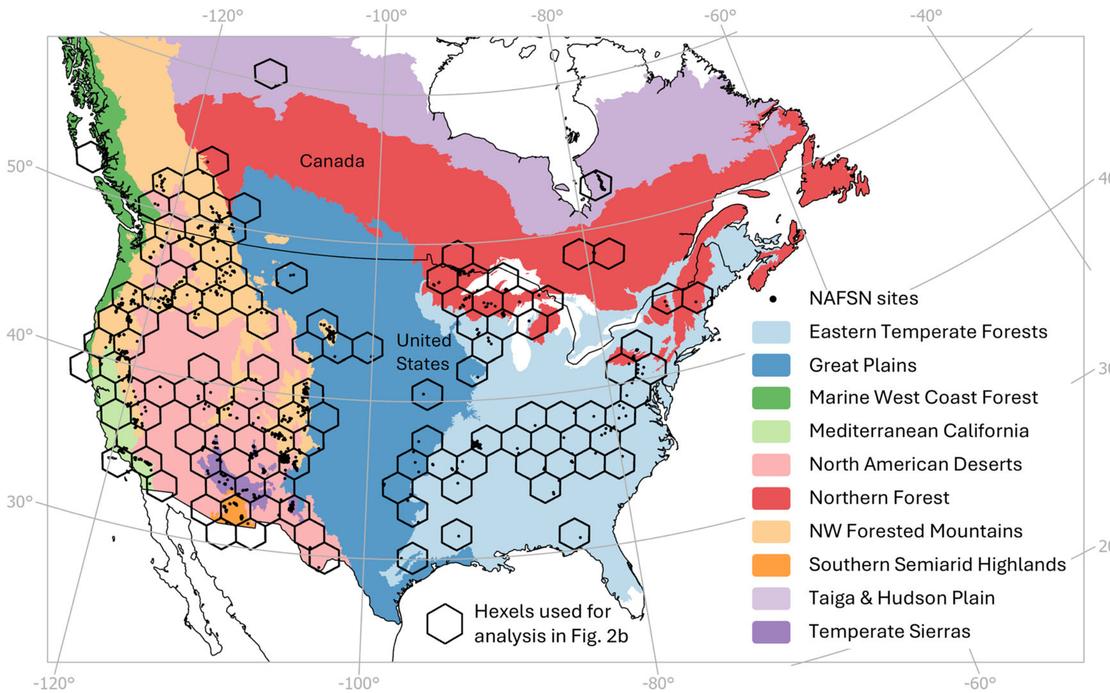

Fig. 1 | Map shows the North American tree-ring fire-scar network (NAFSN)[29] sites used in this study. Also shown are ecoregions and the 120 hexagonal polygons ('hexels') used in our analyses. Hexel dimensions: 200 km diameter; 34,641 km^2.

Table 1 | Observed *vs.* expected number of times NAFSN sites burned from 1984–2022

Ecoregion	Observed number of times burned (O)	Expected number of times burned (E)	Percent of expected (O/E)
Eastern Temperate Forests (92 sites)	63	450	14
Great Plains (26 sites)	36	56	64
Mediterranean California (39 sites)	43	77	56
North American Deserts (96 sites)	52	243	21
Northern Forests (155 sites)	3	281	1
NW Forested Mountains (1097 sites)	426	2281	19
Southern Semiarid Highlands (188 sites)	252	516	49
Taiga & Hudson Plain (35 sites)	51	32	159
Temperate Sierras (122 sites)	63	543	12
All sites ($n = 1851$)	989	4346	23

The expected number of times burned is based on the mean annual proportion of sites that burned during the historical period (pre-1880). The difference between the observed and expected number of times burned is statistically significant ($p \le 0.05$) in all ecoregions, noting that the only ecoregion with a higher observed number of times burned than expected is the Taiga & Hudson Plain
NAFSN North American tree-ring fire-scar network.

periods. These hexel-based results show that an average of 5% burned in 2011 and 2021, whereas 17% burned in 1748 (Fig. 2b); an average of 7% burned per year during the 1600–1880 historical period. Similar patterns emerged for NAFSN sites grouped by ecoregion (Fig. 3). In the NW Forested Mountains ecoregion, for example, a maximum of 8% of sites burned during the contemporary period in 2021, yet 23% of sites burned in 1729 and 1748 (Fig. 3e); an average of 5% of sites burned annually in the historical period in the NW Forested Mountains ecoregion (Table 2).

The most widespread contemporary fire year(s) had significantly fewer sites burned ($p \le 0.05$) than the historical prevalence of such occurrences across all NAFSN sites and the majority of ecoregions (Table 2). For example, while 6% of all NAFSN sites burned in 2020 (the maximum observed from 1984–2022), ≥ 6% of sites burned in 37 out of every 100 years, on average, under the historical reference period (Table 2). From an ecoregional perspective, the most widespread contemporary fire year in the NW Forested Mountains occurred in 2021 (8% of sites burned), and in the Temperate Sierras occurred in 2012 (8% of sites burned), yet from 1600–1880, such fire years occurred in at least 20 out of every 100 years, on average (Table 2 and Fig. 3). No significant differences in the likelihood of widespread fire years between contemporary and historical periods were observed in the Great Plains, Mediterranean California, and Taiga & Hudson Plain ecoregions (Table 2).

The prevalence of non-fire years occurred significantly more often ($p \le 0.05$) in the contemporary period than in the historical period across all NAFSN sites and most ecoregions (Table 3). Specifically, the occurrence of non-fire years at all NAFSN sites in the contemporary time period was >100 times more prevalent compared to the historical period and at least five times more prevalent in the Northern Forests, Temperate Sierras, and Eastern Temperate Forests ecoregions (Table 3). The ratio of contemporary to historical likelihood of non-fire years is likely understated in most ecoregions, given that the relatively low sample size in the first few decades of the historical time period (Fig. S3) may inflate the historical likelihood of non-fire years.

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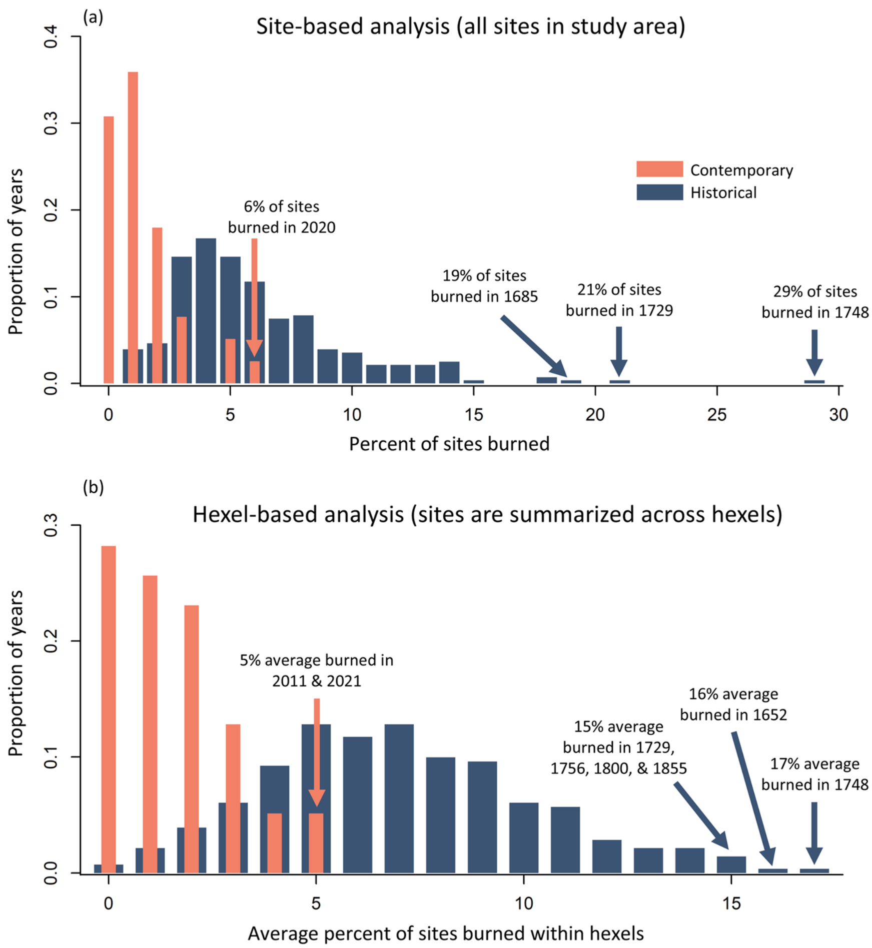

Fig. 2 | Comparison of the distributions of fire occurrence in the historical (pre-1880) and the contemporary (1984–2022) periods for all North American tree-ring fire-scar network (NAFSN) sites in the United States and Canada. Analyses show the percent of NAFSN sites burned (**a**) and the average percent of sites burned within hexels (**b**) (see Fig. 1 for hexel map). For reference, 6% of NAFSN sites burned, on average, in the historical period (**a**; Table 2) and an average of 7% of sites burned, among hexels, in the historical period (**b**).

Table 2 | Contemporary (1984-2022) widespread fire years when the largest number of NAFSN sites burned, the maximum percent of sites burned during the contemporary period, the average percent of sites burned in the historical reference period (to show what an average year was prior to 1880), and the historical prevalence of widespread contemporary fire year

Ecoregion	Most widespread year(s) (contemporary)	Maximum % sites burned (contemporary)	Average % sites burned (historical)	Historical prevalence of widespread contemporary fire year
Eastern Temperate Forests	2019	6	13	0.85*
Great Plains	2012	19	6	0.05
Mediterranean California	1985, 2017	20	5	0.02
North American Deserts	2011	10	6	0.18*
Northern Forests	2008, 2015, 2018	1	5	0.89*
NW Forested Mountains	2021	8	5	0.20*
Southern Semiarid Highlands	2020	22	7	0.09*
Taiga & Hudson Plain	1989	74	2	0
Temperate Sierras	2012	8	11	0.54*
All sites	2020	6	6	0.37*

The historical prevalence of widespread contemporary fire year represents the proportion of historical years when an equal or greater number of sites burned when compared to the maximum contemporary sites burned. Historically, widespread fire years (as defined by the contemporary time period) were more frequent ($p \leq 0.05$; *) in most ecoregions, with the exception of Great Plains, Mediterranean California, and Taiga & Hudson Plain.

NAFSN North American tree-ring fire-scar network.

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Discussion

Our study of 1851 tree-ring fire-scar sites and contemporary fire perimeters across the United States and Canada reveals a substantial, persistent fire deficit from 1984–2022 in many forest and woodland ecosystems, despite recent increases in burning. Contemporary fire occurrence is still far below historical (1600–1880) levels at NAFSN

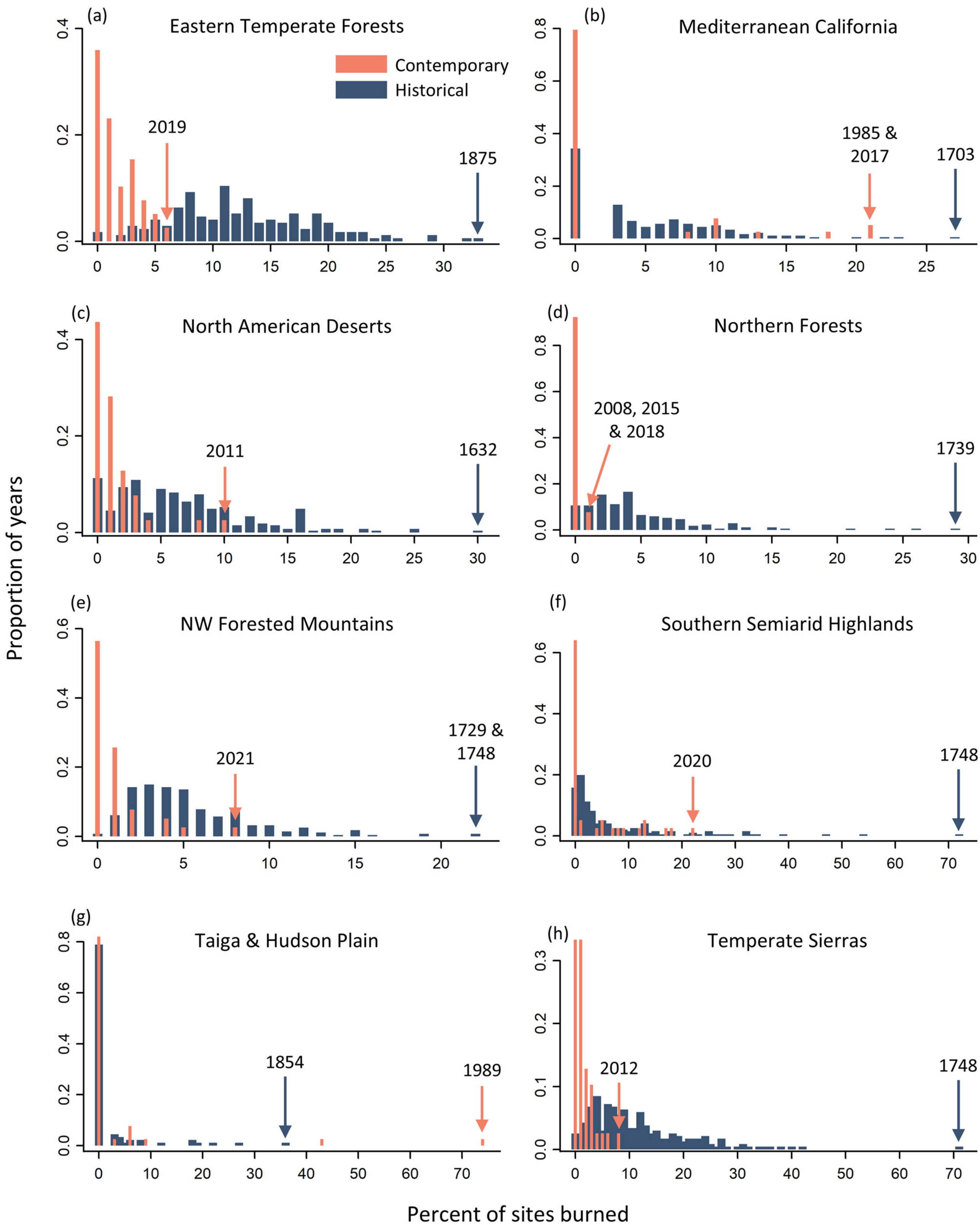

Fig. 3 | Ecoregional distributions of fire occurrence in the historical and contemporary periods. Percent of fire-scar sites burned in the historical (pre-1880) and contemporary (1984–2022) time periods for each ecoregion: Eastern Temperate Forests (**a**), Mediterranean California (**b**), North American Deserts (**c**), Northern Forests (**d**), NW Forested Mountains (**e**), Southern Semiarid Highlands (**f**), Taiga & Hudson Plain (**g**), and Temperate Sierras (**h**).

Table 3 | Historical (pre-1880) and contemporary (1984-2022) representation of non-fire years (i.e., years in which zero sites burned), shown as a proportion of all years in each time period, as well as the ratio between them (odds ratio C/H: contemporary/historical)

Ecoregion	Contemporary proportion of years when zero sites burned (C)	Historical proportion of years when zero sites burned (H)	Ratio (C/H)
Eastern Temperate Forests	0.36	0.02	18.0*
Great Plains	0.54	0.47	1.1
Mediterranean California	0.79	0.34	2.3*
North American Deserts	0.44	0.11	4.0*
Northern Forests	0.92	0.11	8.4*
NW Forested Mountains	0.18	0.00	> 100*
Southern Semiarid Highlands	0.64	0.16	4.0*
Taiga & Hudson Plain	0.82	0.79	1.0
Temperate Sierras	0.33	0.03	11.0*
All sites	0.03	0.00	> 100*

In most ecoregions, the contemporary proportion of a non-fire year was significantly higher ($p \leq 0.05$; *) compared to the historical reference period. When the historical proportion was zero, the odds ratio equals infinity, indicated here as '> 100'.

sites despite multiple large and 'record-breaking' recent fire years, such as 2020 in the western United States. Individual years with particularly widespread fire during the 1984–2022 period were not unprecedented in comparison with the active fire regimes of the historical period across most of the study region. Historically, fires in particularly active fire years were spatially more widespread and ubiquitous compared to fires burning during active contemporary years (Fig. S4). The fire deficit from 1984–2022 only adds to the fire deficit that accrued during the late 19th and 20th centuries[5,7,26,46], which has resulted in well-documented fuel accumulation and increases in canopy density across many forest types in North America[1,47]. While our results suggest that the area burned by wildfires during the last few decades remains relatively low considering the historical prevalence, an accumulating body of evidence indicates that the nature of the wildfires and fire regimes in forests and woodlands has changed substantially--notably with respect to increased wildfire severity[17,48–51].

Many studies have reported increases in area burned associated with a warming climate over the last few decades across much of North America[9,10,40,52–55]. Considering these studies, forest managers and the general public may be surprised to learn that a significant fire deficit persists in many forested ecosystems even as contemporary socioeconomic fire impacts are increasing. Our evidence indicates that, even under a warming climate, the rate at which NAFSN sites burned in recent decades has been much lower than historical rates across most of the continent. We attribute this disparity to aggressive fire suppression, disruption of traditional burning, and forest loss and fragmentation from land development and other land uses (e.g., conversion of forests and woodlands to agriculture). Although the substantial reduction in contemporary fire activity compared to historical time periods may seem desirable, it has greatly altered forest composition, structure, and continuity, in many respects adversely. Largely due to these changes, and compounded by climate change, the inevitable wildfires that do occur are often burning with deleterious impacts on forest ecosystems, human communities, and human health (Fig. 4)[56–58].

The widespread fire deficit at NAFSN sites should not be conflated with fire severity or other ecological impacts, which have trends that are in distinct contrast in many ecosystems. In many western North American forests, particularly those represented by the tree-ring fire-scar sites analyzed here, heavy fuel loads and increased fuel continuity have developed because of fire exclusion[1], thereby increasing fire severity when forests inevitably burn[17,48]. Contemporary fires include more high-severity fire (i.e., high tree mortality) as a proportion of total area burned, and high-severity patches are becoming larger and more connected[59,60]. As a cascading effect, some forests are converting to non-forest vegetation types as they experience unprecedented levels of severe fire, particularly when combined with uncharacteristic short-interval high-severity reburns, increased patch sizes of high-severity fire, and climate change[61–63]. In many cases, this ecosystem reorganization and forest loss is driven by combinations of tree mortality and recruitment failure[64,65], which can lead to irreversible tipping-point conversions in the context of changing climate[66,67]. This results in undesirable effects on valued resources including old-growth trees, human infrastructure, water quality, and habitat for sensitive and endangered species[59,68,69]. Therefore, even though less fire is occurring than expected under a historical fire regime, contemporary fires are likely unprecedented when viewed through the lens of their severity and ecological impacts.

In portions of eastern North America, reduced burning over the last century in fire-adapted, flammable oak-pine woodlands and forests has resulted in encroachment of shade-tolerant, fire-sensitive tree species (mesophication)[3]. In these increasingly dense forests, shaded conditions, mesophytic litter, and an increasing abundance of species that inhibit the regeneration of the formerly dominant species make the vegetation less flammable[70]. This reduces the likelihood of spreading fire in the future and potentially threatens the viability of fire-adapted species. However, pronounced droughts still cause some eastern forests to burn; the resulting fire effects can be uncharacteristically severe, as was seen following wildfires associated with extreme fire weather in the southern Appalachian Mountains during 2016[71]. Fire exclusion in other eastern forests has also led to an unprecedented abundance of ericaceous shrubs, which presently form extensive thickets in the understory of the xerophytic pine stands that are the source of many fire-scarred trees[3]. These shrubs can be extremely flammable and contribute to intense wildfires that endanger human infrastructure in the wildland-urban interface (WUI). Post-fire resprouting of shrubs, and their inhibition of tree regeneration, may portend a structural shift from tree to shrub dominance over the long term for many sites[49].

The detrimental impacts of contemporary wildfires on human lives, infrastructure, air quality, and communities have unquestionably increased over the past decades[72,73], exemplified by numerous wildfires in recent years that have devastated communities (e.g., Fort McMurray, Alberta [2016], Gatlinburg, Tennessee [2016], Paradise, California [2018], Detroit, Oregon [2020], Jasper, Alberta [2024]). The enormous and unprecedented socioeconomic impacts of these recent fires may seem counter to our overall finding that a substantial fire deficit persists across many forest types across our study region. Here, we offer

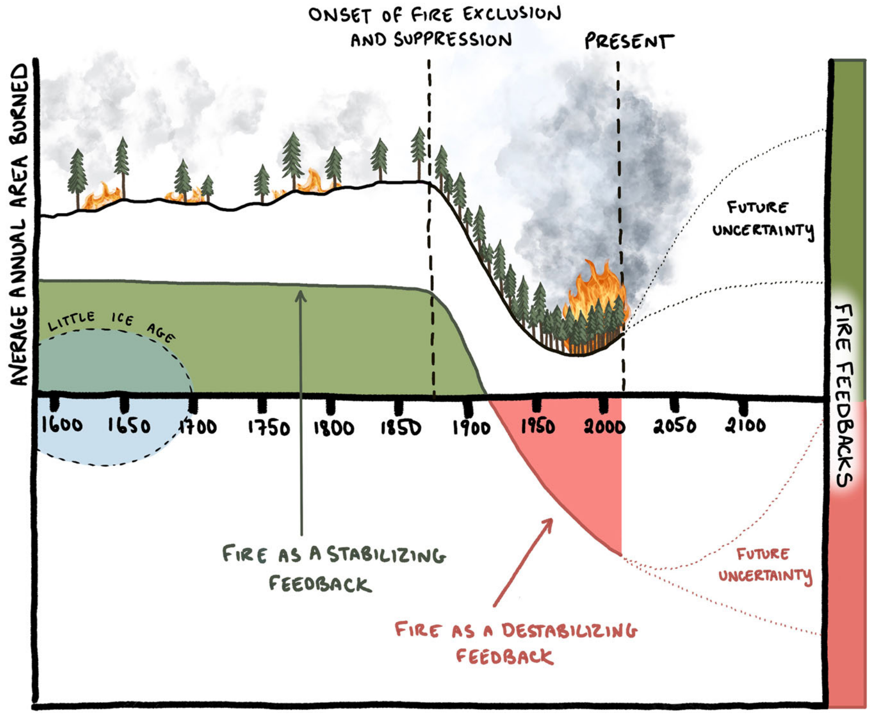

Fig. 4 | Conceptual figure illustrates the impacts of fire exclusion and suppression on area burned and fire severity in historically frequent-fire North American forests and woodlands represented by the majority of the fire scar sites used in our analysis. This conceptual model generally applies to dry conifer forests in western North America, formerly red pine dominated forests in the southeastern boreal forest, and temperate broadleaf and conifer woodlands and forests of the eastern United States. Prior to ~1880, traditional burning and lightning-ignited fires contributed to an active historical fire regime with frequent, lower-severity fires that produced tree-ring fire scars, cumulatively burned a relatively large area, and maintained low fuel loads, thereby serving as a stabilizing (negative) feedback[88]. The gradual increase in annual area burned from 1600 to 1880 may have resulted from a warming climate at the end of the Little Ice Age[136] and is generally based on Marlon et al.[7], although this pattern may manifest due to reduced records in the earlier periods of analysis[137]. The onset of sustained fire exclusion and suppression over many decades reduced annual area burned, reflected by a decline in tree-ring fire scars, during which time fuel loads accumulated. At present, fires generally burn during pronounced droughts, increasing the area burned in recent years, although total area burned remains below historical levels. Contemporary fires in historically frequent fire forests now often act as a destabilizing (positive) feedback[88], with tremendous social-ecological effects through smoke impacts, reduced community safety, and diminished forest recovery. The future is uncertain and depends on management actions, social decisions and priorities, and climate change. Figure credit: Jessie Thoreson.

some additional context to these seemingly counterintuitive findings (Fig. 4). First, the rapid expansion of the WUI[74–76] means that contemporary fires interact with a more extensive and vulnerable built environment than was present during the historical period[33,77,78]. Second, many contemporary communities are, in a sense, ill-adapted to wildfire compared to traditional communities around which frequent, low-intensity burning historically occurred[79–83]. Traditional burning was designed both to manage valuable resources and to attenuate fire risks to communities. Most contemporary human ignitions, on the other hand, are often unplanned and can have outsized adverse or even harmful effects on human communities[73,84,85]. Third, the unprecedented combinations of fuel loads, weather, and climate create conditions in which some fires defy all suppression efforts, thereby increasing risk to communities and forests[77,86,87].

Overall, the relationship among fire, forests, and people has changed substantially between the historical (1600–1880) and contemporary (1985–2022) time periods across much of Canada and the United States. Historically, particularly at the sites represented by the fire-scar data used in this study, fire often served as a stabilizing (or negative) feedback[88,89] for forests and people (Fig. 4), in which frequent fire consumed live and dead fuel, thereby perpetuating a fire regime dominated by low- to moderate-severity fire and selecting for tree species that could tolerate frequent fire[66] (and therefore record fire scars). These fires, some of which were intentionally ignited by Indigenous peoples, often had beneficial outcomes for people and societies in that they were used to promote certain foods and reduce the potential for undesirable fire[81]. Conversely, contemporary fires are more often acting as a destabilizing (positive) feedback[88,89] for forests and people. For example, contemporary fire is more frequently acting as a catalyst for ecological transformation or vegetation type conversion[62,90] and often causes great harm to society[87,91], as previously described. Not all contemporary fires have this destabilizing effect, but our relationship with fire has changed so that many if not most fires are destabilizing to forests and/or people (Fig. 4).

We show that many forest types across North America exhibit a persistent fire deficit, but it is important to reiterate that our study is focused on sites where fire scar data have been collected. Some regions are under-sampled for various reasons including fire regimes that do not generally support fire-scar formation (e.g., much of the boreal forest, which naturally experiences predominantly high-intensity crown fire, and non-forest areas such as the North American Great Plains), limits to available research funding, and evidence lost through land-use conversion and decomposition of fire-scarred stumps, dead trees, and downed logs. Consequently, our findings may not comprehensively reflect differences in contemporary vs. historical fire, especially in areas where fire-scar data are not available. For example, more fire than might be expected under a historical fire regime (i.e., a fire surplus) has been noted in non-forested regions such as the Great Basin shrublands[92] and tundra[93]. Moreover, some forest regions have limited fire-scar data, yet they have burned extensively in recent decades, notably the western portions of the Northern Forests and Taiga & Hudson Plain ecoregions (Fig. S1). Although our methods and existing data do not permit us to evaluate contemporary vs. historical fire activity in these areas, some studies using palaeoecological data indicate that contemporary burning has surpassed historical levels[24,94]. It is also worth noting that a statistically significant fire surplus was documented in the Taiga and Hudson Plain ecoregion (Table 1); given the concentrated nature of the NAFSN sites in this ecoregion (Fig. 1) and the reduced timeframe of the historical period (Fig. S3), we limit discussion of this finding. Yet, years such as the 2023 Canadian fire season, which exceeded the average contemporary area burned by seven times (15 Mha in 2023 vs. 2.1 Mha on average, 1986–2022[95]) and more than doubled the prior contemporary record for national annual area burned (6.7 Mha in 1989[96,97]), offer a bleak view of the potential for future fire activity under a warmer climate in these regions with abundant fuels. Increasingly frequent and severe fire in the boreal biome of North America has caused an ongoing continental-scale decline in conifer species dominance, and in some cases, forest regeneration failure[63,98].

The fire deficit documented in our study would seem to present an insurmountable obstacle to forest managers striving to restore forests to their historical fire-resilient state. Excessive fuel loads, climate change, and a rapidly expanding wildland-urban interface compound this challenge; however, land managers in some areas are demonstrating that a restored fire regime is achievable. For example, frequent prescribed fire is widely applied in some temperate forests, especially in the southeastern United States where frequent burning is an accepted practice. The Eglin Air Force Base in Florida serves as an example, where longleaf pine forests now experience fire return intervals within their historical range (1–10 years)[99,100]. Other areas that closely resemble historical fire frequency include the Tall Timbers Research Station in Florida[101], small areas in the southern Appalachian Mountains[102], landscapes across the Ozark and Ouachita Mountains[103], and the Flint Hills in Kansas[104]. In western North America, some Tribal nations[105,106] and federal land managers of large contiguous protected areas have managed active fire regimes approaching historical reference conditions. Landscape-scale, relatively frequent fire has been restored to forests in the Gila Wilderness in New Mexico, the Saguaro Wilderness in Arizona, and portions of Yosemite National Park[107–109]. These areas experienced a period of fire exclusion during the 20th century, although some lightning-ignited fires continued throughout this period. Fire management policy for these protected areas was revised in the 1970s to encourage managed and prescribed fire[109,110]. These natural experiments have demonstrated multiple favorable outcomes from maintaining close to historical fire intervals, including reduced risk of high severity fire[48], improved hydrological function[111], and enhanced biodiversity[112]; in many of these cases, fire is once again acting as a stabilizing feedback (Fig. 4).

We have shown that a pervasive fire deficit remains and that fire occurrence in recent widespread fire years is not unprecedented across many North American forest types according to the multi-century tree-ring record. However, recent fire years are likely unprecedented in terms of highly elevated fire severity (e.g., tree mortality and soil damage)[48], recent fire-catalyzed forest conversions[62], and impacts to humans[73]. Overall, the deleterious impacts of contemporary fires on humans and ecosystems are facilitated by the growing fire deficit that has removed the self-regulating behaviors and stabilizing feedbacks of historical fire regimes (Fig. 4). As several recent fire years have shown, current forest conditions, human infrastructure, and many communities are not well-equipped to endure the extreme behavior characteristic of emerging fire regimes[1,91,113]. Without substantial investments in proactive fire management, these impacts to forests and humans are likely to intensify in future decades as fuels continue to accumulate, particularly when compounded by climate change[67,86]. There is strong consensus within the scientific community that landscape-level restoration and fuels reduction, defensible space, community hardening, and resumed fire regimes are necessary to increase forest and community resilience to the next inevitable fire[1,114,115]. Specific actions include substantial increases (10- to 100-fold) in prescribed fire, mechanical thinning combined with prescribed fire, and managing fire as an ecosystem process in locations and times of year when it is safe to do so[42,116]. Such preemptive actions will increase the probability that future unplanned fires will be less disruptive to society and forest ecosystems (i.e., lower severity fire)[117], thereby allowing us to better co-exist with fire[118,119], as did traditional societies long before the disruption of historical fire regimes[45,81,82,120,121].

Methods

Historical and contemporary fire data

We used the North American tree-ring fire-scar network (NAFSN)[29] to characterize historical (pre-1880) fire occurrence. Historical fires are documented using annually resolved tree-ring fire-scar dates on individual living or dead trees, stumps, or logs that were sectioned and processed according to the standards of dendrochronology[122]. Site-level composite fire history records are generally derived from multiple trees from plots (~1 ha) to forested stands (~500 ha) that incorporate the longest and most complete census of fire dates obtainable from the available material[108]. Here, a site is considered burned if at least two trees and 10% of trees recorded fire in a given year; this filter captures the occurrence of spreading fires, compensates for the incomplete record found on individual trees, and excludes non-fire scarring events such as mechanical tree damage or individual tree lightning strikes[123,124]. 1,851 NAFSN sites met this criterion. We used data from the years 1600 to 1880 as our historical period. Our starting period begins in 1600 because the sample density and geographic distribution of fire-scar data limits analysis prior to ~1600[29]. For consistency across the study area, we used 1880 as the historical period end date even though the effective date of fire exclusion varies across the continent, starting around 1880 in the western portions of our study area[125] and even later in the eastern portions[126,127], as post-colonization traditions of burning persisted in many parts of the eastern United States (US) until the early 1900s[45]. However, as some ecoregions were data-limited even after 1600 (Fig. S3), we used a ruleset to establish a starting year: the historical reference period for each ecoregion begins when at least 100 sites or 25% of all sites are recording the presence/absence of fire. The start of this historical reference period ranges from 1600 (all NAFSN sites combined and NW Forested Mountains ecoregion) to 1791 (Taiga & Hudson Plain ecoregion) (Fig. S3).

We characterized contemporary fires using detailed fire perimeters derived from remote sensing imagery that is available for 39 years (1984–2022; Fig. S1). In Canada, we obtained 1984–2020 fire perimeters from the Canadian National Fire Database[128] and 2021–2022 fire perimeters from the National Burned Area Composite[96,97]. In the US, we obtained 1984–2021 fire perimeters ≥ 200 ha in the eastern US and ≥ 400 ha in the western US from the Monitoring Trends in Burn Severity program[129] and 2022 fire perimeters (applying the same size thresholds for consistency within the US) from the Wildland Fire Interagency Geospatial Services Group[130]. Small fires in the US are missing in our analyses (fires < 400 ha and < 200 ha are excluded in the western US and eastern US, respectively), but this likely has negligible influence on our findings given that the vast majority of contemporary area burned results from larger fires[131,132].

The ecoregions used in our study (Fig. 1) are intended to represent a diversity in forest types. However, we acknowledge that there is variation in forest types and dominant tree species within ecoregions and that some forest types may occur across multiple ecoregions. For example, in viewing the fire-scarred tree species across our study area, ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) are found in most or all western US ecoregions, post oak

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(*Quercus stellata*) and shortleaf pine (*Pinus echinata*) are found in the Eastern Temperate Forests Ecoregion, lodgepole pine (*Pinus contorta*) is present in the northwest portion of our study area, and red pine (*Pinus resinosa*) in the northeast portion of our study area (Fig. S2). Fire scars were recorded by over 70 species in this study.

Assessing fire deficit or surplus

To determine whether there was a contemporary fire deficit or surplus (or no significant departure) across all NAFSN sites and within each ecoregion, we calculated the 'expected' number of times NAFSN sites would have burned during the 39-year contemporary period (1984–2022) based on the mean annual proportion of sites that burned during the historical reference period. For example, if 5% of sites burned annually (on average) in a given ecoregion during the historical reference period, and the ecoregion had 150 NAFSN sites, we would expect the sites to have collectively burned 292 times from 1984–2022 (0.05 burned × 150 sites × 39 years = 292 times burned).

We then measured the observed number of times burned by counting NAFSN sites that annually intersected contemporary fire perimeters from 1984–2022 cf. [124]. In doing so, we effectively assume a 100% fire recording rate in the contemporary time period, even though we might be overestimating the number of sites burned because of undetected and unmapped unburned patches. Coupled with the recording rate in the historical time period being <100%, we are likely underestimating any observed fire deficits or other metrics analyzed in this study. Recognizing that larger sites (in terms of area sampled) are likely to record more individual fire events than smaller sites[133,134], we buffered all NAFSN sites based on sampled area: we converted all NAFSN sites (X and Y coordinates) to circular polygons of varying sizes reflecting the area that was sampled (if known). In cases where sample area was unknown (26% of sites), we assigned that site an area corresponding to the 75th percentile from the distribution of known sampled areas. In all analyses, if a circular NAFSN polygon intersected any contemporary fire perimeters, the NAFSN site was considered burned during those fire events (Fig. S5).

We compared the expected and observed number of times burned and tested for significant differences using a bootstrapping procedure. Specifically, we drew 1000 random samples spanning 39 continuous years (the length of the contemporary fire record) from the historical fire data, calculated the mean annual proportion burned, calculated expected times burned, and produced 95% confidence intervals (CIs) of these for all NAFSN sites in the US and Canada combined and for each ecoregion. Random 39-year samples can 'wrap' from 1880 to the beginning of the historical reference period when the random starting year is 1842 or later. Statistical significance ($p \leq 0.05$) was inferred if the observed number of times burned for contemporary fires did not overlap with the 95% CIs.

Comparing individual contemporary fire years to the historical reference period

To determine whether recent fire years are unprecedented when compared to the historical reference period, we created frequency distributions showing the annual percent burned of all NAFSN sites and within ecoregions (Fig. 1). We then plotted frequency distributions depicting the annual percent of NAFSN sites intersecting contemporary fire perimeters. To address the varying density of fire-scar sites across our study region, we conducted a parallel analysis summarizing historical and contemporary fire within hexagonal polygons (hereafter 'hexels'; 200 km diameter, 34,641 km^2; Fig. 1). To do so, we summarized the percent of NAFSN sites that burned per year within each hexel, then averaged these values for each year across all hexels in the US and Canada ($n = 120$; Fig. 1) and produced frequency distributions for historical and contemporary time periods. Hexels were thereby given equal weight, regardless of how many NAFSN sites intersected each.

We conducted two additional analyses across all NAFSN sites and each ecoregion focusing on contemporary years in which (a) the highest number of sites burned and (b) zero sites burned (hereafter 'non-fire years'), which we compared to the historical prevalence of each of these occurrences. To do so, we calculated how often, as a proportion of years, the contemporary maximum percent of sites burned was met or exceeded in the historical reference period. We then calculated the proportion of years over the sample periods that were non-fire years and then divided the contemporary prevalence by the historical prevalence, resulting in the ratio between the two. To determine statistical significance, we used the block bootstrapping sampling technique described above ($n = 1000$), 'wrapping' permitted, and calculated the prevalence of (a) the most widespread fire years and (b) non-fire years for each sample. We considered the difference between historical and contemporary fire to be significantly different ($p \leq 0.05$) when the CIs of the bootstrap sampling did not overlap with the observed contemporary prevalence of the most widespread fire year or zero sites burning.

Data availability

No data were generated for this study. Fire perimeter data from the United states are publicly available from the Monitoring Trends in Burn Severity program (http://www.mtbs.gov) and the Wildland Fire Interagency Geospatial Services Group (https://data-nifc.opendata.arcgis.com/datasets/nifc::wfigs-current-interagency-fire-perimeters/about). Fire perimeters from Canada are publicly available from the Canadian National Fire Database (https://cwfis.cfs.nrcan.gc.ca/ha/nfdb) and National Burned Area Composite (https://cwfis.cfs.nrcan.gc.ca/datamart/metadata/nbac). Approximately half of the fire scar data are publicly available from the International Multiproxy Paleofire Database (IMPD) (https://www.ncei.noaa.gov/products/paleoclimatology/fire-history). The remainder are actively being contributed to the IMPD via the North American Fire Scar Synthesis project (https://www.ncei.noaa.gov/access/paleo-search/study/34853).

Code availability

No specialized code was developed for this study. All fire-scar data processing was conducted in the R burnr library[135].

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S.A.P., C.H.G., E.Q.M., and R.A.L. conceived the project. S.A.P. and E.W. developed the methodology. S.A.P., M.L., and C.H.G. conducted formal analysis. S.A.P., M.L., E.W., and L.D.D designed and produced the tables and figures. S.A.P., C.H.G., E.Q.M., M.L., E.W., J.T.A., D.A.F., J.D.J., L.D.D., C.W.L., R.A.L., K.F.K., C.E.N., M-A.P., J.P., M.C.S., A.P. Williams, A.P. Wion, and L.L.Y. interpreted the findings and suggested methodological improvements. S.A.P. wrote the original draft, with the remaining authors providing critical feedback and edits.

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