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Contemporary fires are less frequent but more severe in dry conifer forests of the southwestern United States

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Wildfires in the southwestern United States are increasingly frequent and severe, but whether these trends exceed historical norms remains contested. Here we combine dendroecological records, satellite-derived burn severity, and field measured tree mortality to compare historical (1700-1880) and contemporary (1985-2020) fire regimes at tree-ring fire-scar sites in Arizona and New Mexico. We found that contemporary fire frequency, including recent, record fire years, is still <20% of historical levels. Since 1985, the fire return interval averages 58.8 years, compared to 11.4 years before 1880. Fire severity, however, has increased. At sites where trees historically survived many fires over centuries, 42% of recent fires resulted in high tree mortality. Suppressed wildfires tended to burn more severely than prescribed burns and wildfires managed for resource benefit. These findings suggest that expanded use of low-severity prescribed and managed fire would help restore forest resilience and historical fire regimes in dry conifer forests.

Changing fire regimes pose mounting challenges to both natural and human systems. Intensifying wildfire activity associated with climate change is exerting increasing pressure on a wide range of forest ecosystems globally[1–3]. Where fire activity exceeds the range of conditions for which species are adapted, fires can drive local population extirpations and trigger ecosystem shifts[4]. Increasing fire *frequency* can dramatically alter forest population dynamics, in particular when the time between successive, tree-killing fires is not sufficient for recovering tree species to achieve reproductive maturity[5,6]. Increasing fire *severity* can drive anomalous tree mortality, even for the most fire-tolerant tree species (e.g., giant sequoia [*Sequoiadendron giganteum*])[7], thereby reducing propagule availability in high-severity patches and impeding recovery[8,9]. Severity in this context encompasses both immediate and delayed effects to vegetation as measurable post-fire through satellite- or field-based metrics[10,11]. However, the reduction or elimination of fire—often imparted by human fire exclusion—can also result in major ecological changes. For example, the loss of fire due to elimination of cultural burning practices, land use changes such as grazing that limits fire spread, and fire suppression have all greatly increased abundance of woody plants and fuels, altered species composition, and homogenized forest communities across North America and elsewhere[12–14]. Accordingly, understanding the extent and direction of contemporary fire regime departures from historical norms can provide critical insight into patterns of ecosystem changes and vulnerabilities, and inform conservation and management interventions.

Dry conifer forests in the American Southwest dominated by ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) are particularly vulnerable to the combined effects of altered fire regimes and climate change. A large body of evidence demonstrates that many of these forests were historically characterized by frequent, low- to moderate-severity fires associated with prolonged dry seasons, profuse grassy fuels, and abundant ignitions from lightning and Indigenous land stewardship[15–18]. These fire regimes were disrupted by Euro-American colonization in the late nineteenth century, producing an enduring fire deficit[19] and initiating fuel build up[20]. However, recent decades have been marked by a return of fire to dry southwestern forest landscapes. Increased fuel availability and continuity, combined with increasingly long fire seasons and dry fuels[21,22] and abundant human ignitions[23], have dramatically escalated wildfire activity, including extent of high-severity fire[24–26]. Compounded by warming and drying post-fire conditions, extensive high-severity fires are constraining regeneration by wind-dispersed conifers[8,27–31] and in some areas are catalyzing persistent conversion to non-forest vegetation types[32,33].

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Although these processes are generally well understood, the extent to which contemporary fire regimes differ from historical norms in dry southwestern forests of the US remains the subject of continued debate, with divergent interpretations leading to important implications for forest management[34–36] One viewpoint has relied largely on data from General Land Office (GLO) surveys to reconstruct late nineteenth century stand structure based upon tree age-size relationships and forest density extrapolations, which were then interpreted to reconstruct fire severity[35]. These authors suggest that high-severity fire was common and widespread in dry forest systems long before the prominent ecological changes of the last century, and thus modern severe wildfires do not exceed historical norms[34]. If severe contemporary wildfires in fact represent historically normal events, then management efforts intended to reduce fire severity, including thinning of small-diameter trees, fuels reduction treatments, and low-severity prescribed burns, could appear to be ecologically unsound. In contrast, the weight of evidence holds that modern, high-severity wildfires are outside of historical fire regime norms in these forest types[36]. This view is based upon many lines of widely replicated evidence, including large increases in tree density coincident with fire exclusion over the last century documented through comparisons between historical reconstructions and modern measurements of forest structure[12,37], a paucity of documentary and scientific evidence of high-severity fire occurring in dry conifer forests in the eighteenth and nineteenth centuries[38,39], and abundant evidence of frequent, low-severity fires in the historical tree-ring fire-scar record[40–42]. Under this view, management efforts to reduce tree densities and fire severity may be essential to sustaining dry forest systems. In light of this disagreement, an improved quantification of the differences between historical and contemporary fire frequency and severity would be useful in assessing forest vulnerabilities and setting management priorities[43], particularly as forest vulnerability to severe fire-driven vegetation conversions is expected to increase under future climate[32].

Two distinct lines of evidence—dendroecology and remote sensing—are widely used to characterize patterns of historical and contemporary fire activity, respectively. Tree-ring analysis of fire-scarred trees has been used as a primary means of characterizing the fire frequency, severity, seasonality, and extent of historical fire occurence[18,42,44]. Fire-scarred trees are unequivocal evidence of low-severity fire at a particular place and time and can record dozens of fires over centuries. Aggregating these records from plots to forested landscapes to the southwestern US has been instrumental in establishing that frequent, low-severity fire was ubiquitous in dry conifer forests of the region for centuries prior to circa 1900[45–51]. The current tree-ring fire-scar network in the southwestern US includes >400 sites, thousands of fire-scarred trees, and tens of thousands of fire scars, and has been shown to be representative of the range of topographic and climatic conditions of regional dry conifer forests[40]. In contrast, contemporary fire regimes are measured primarily via satellite observations (particularly over the Landsat period of record, 1984-present) and on-the-ground field data collection[10,11]. Field-verified, satellite-derived metrics covering the full range of burn severity have facilitated analyses of recent burning trends in the modern era[26,52,53]. These two types of data—tree-ring fire-scar records and satellite observations—can be brought together to compare historical and contemporary fire frequency and severity. Fire-scar sites stand as a witness to centuries of frequent, low-severity fire. If contemporary fire regimes are not different from those that occurred historically, the satellite record would be expected to show similarly frequent, low-severity fire. However, if dry conifer forests across the region as represented by fire history sites are currently burning less frequently or at high severity, that would provide direct evidence of altered fire regimes.

The purpose of our study is to bring together tree-ring records, satellite imagery, and field measures to ask: *at sites where tree-ring records demonstrate that trees historically survived frequent low-severity fire for centuries, are contemporary fires burning differently?* Specifically, we (1) quantify and contrast historical (1700–1880) and contemporary (1985–2020) fire frequency at 406 fire history sites, comprising thousands of individual trees, sampled prior to contemporary fires (Fig. 1) to assess whether recent fires are occurring at frequencies that approach historical levels. Next, we (2) quantify and contrast historical and contemporary fire severity using satellite-measured burn severity and field data on tree mortality to derive a binary metric of severity: unlikely vs. likely mature tree mortality. Because historical fires left many surviving fire-scarred trees over centuries prior to 1880, with some trees surviving and recording as many as 41 fires over 180 years, it follows that those fires were characterized predominantly by a low probability of tree mortality. We compare observed and satellite-measured fire-related tree mortality at these sites to inferred historical norms. Finally, given the strong rationale for reducing fire severity to sustain southwestern forests under climate warming[27], we were also interested in assessing the extent to which varying contemporary fire management strategies (prescribed burning, managed wildfire, and full suppression, described fully in the "Materials and methods") might be associated with different fire outcomes. Taken together, our findings are intended to bear directly on the appropriateness, or lack thereof, of prescribed burning and managed wildfire to promote low-severity burning of southwestern dry forest ecosystems.

Results

Historical and contemporary fire frequency

Trends in multidecadal fire activity across the full period of record (1700–2020; incorporating both tree-ring fire scars and fires mapped from satellite imagery), show a pronounced decline from historically frequent to near-zero fire for much of the twentieth century, with recent increases yet to equal historical fire occurrence at regional and landscape scales (Fig. 2). Based on averages of fires per decade for all fire history sites, the mean site fire frequency was 0.87 fires per decade from 1700 to 1880 (every 11.4 years). This rate dropped to <0.1 fires per decade between 1880–1985 (equivalent to >100-year fire interval) and rose to an average of 0.17 fires per decade (every 58.8 years) since 2000, though with considerable regional variation (Fig. 2). A comparison of mean fires per decade between the historical and contemporary periods indicates that 14.2% of sites have returned to or exceeded historical frequency since 1985, and 85.8% of sites are burning less frequently than historically.

During the historical period, across all sites, 5150 individual trees recorded an average of 6.6 fires per tree (maximum 41; Supplementary Fig. 1), with 1521 trees recording at least 9 fires. Sites averaged 14.2 fires (maximum 78; Supplementary Fig. 1), with 102 sites recording at least 17 historical fires. During the 36-year contemporary period (1985–2020), 206 sites (50.7%) burned at least one time; 99 sites (24.2%) burned twice or more within that time frame, including 17 sites burning three or more times. One site in the Gila Mountains in New Mexico burned in five fires since 1985 and one site in the Rincon Mountains burned seven times. Contemporary fire occurrence varied by geographic area—generally higher in our field-sampled mountain ranges than elsewhere in the study area—with 55% of sites in the Jemez Mountains and 100% of sites burned in both the Kaibab Plateau and Chiricahua Mountains (Table 1). We were able to classify the type of fire and thus its management strategy for 89 (of 102) contemporary fires. Of those, 56 (62.9%) were suppressed wildfires (burning 243 fire history sites, including reburns), whereas 24 (27.0%) were wildland fire use fires (burning 51 sites) and 9 (10.1%) were prescribed burns (burning 15 sites).

Historical and contemporary fire severity

Of the 406 fire history sites from the North American Fire-Scar Network (NAFSN)[40] used in this study, 206 had burned in the contemporary period, from which we extracted satellite-measured burn severity (given in modeled Composite Burn Index (CBI)). We conducted field surveys of fire effects in plots at 74 of these sites. Because much of the fire-scarred material from which the original fire histories was developed came from stumps and down wood, our goal was not to track the survival of individual trees sampled for fire history, but rather to quantify tree mortality at the plot scale. We were, however, able to locate at least one of the original fire-scar sampled trees, stumps, or logs at 25 sites (33.8%; see Supplementary Fig. 2 for images of fire-scarred stumps and trees). We found a range of fire effects at the field

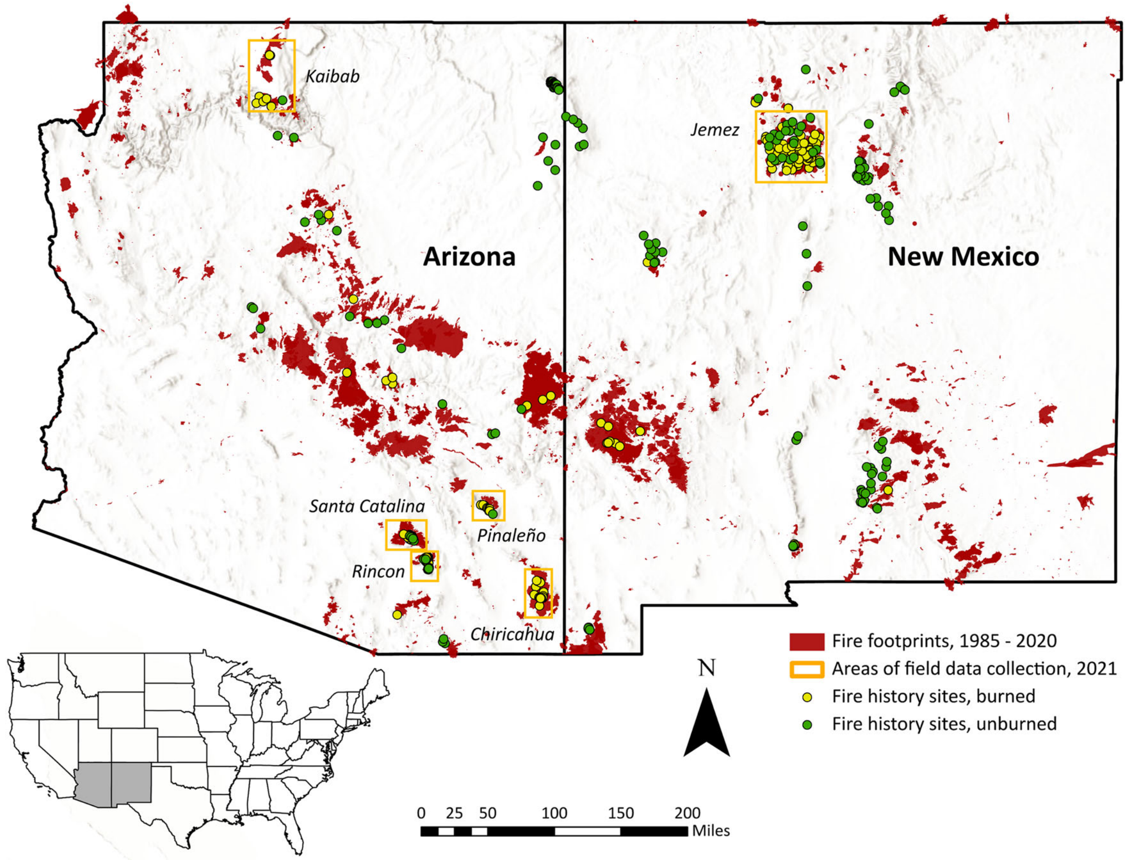

Fig. 1 | Study area map showing locations of 406 tree-ring fire history sites in the southwestern United States analyzed in this study and contemporary fire history (1985–2020). Burned and unburned designations refer only to defined contemporary period.

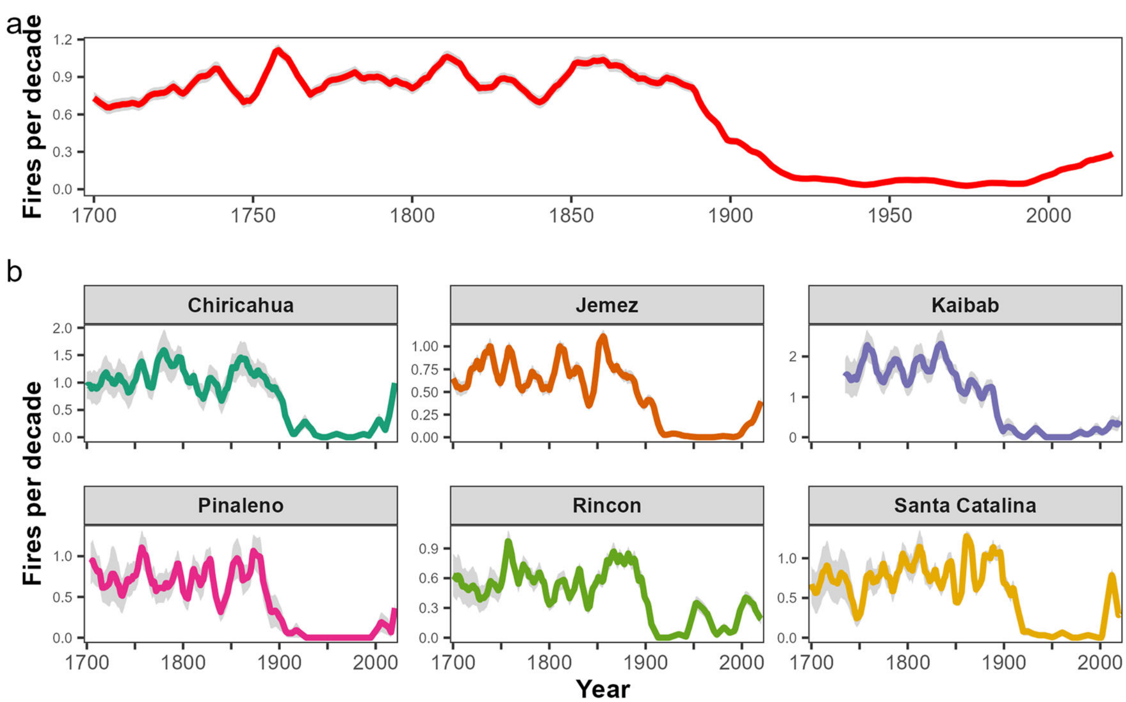

Fig. 2 | Regional and landscape fire frequency in dry conifer forests of the southwestern United States from 1700 - 2020. Smoothed 21-year moving average of mean number of fires per decade for **a** all tree-ring fire history sites in the southwestern United States (n = 406) and **b** geographic areas targeted for field sampling (n = 226 total sites). The time series were created by combining tree-ring fire-scar records with contemporary fire perimeter data. Gray shading shows the standard error of mean fires per decade.

Table 1 | The number of tree-ring fire-scar sites, field plots, contemporary fires, and the percent of tree-ring fire-scar sites burned from 1985–2020 in the southwestern US and sub-regions

Geographic area	Tree-ring fire-scar sites	Field plots	Fires 1985–2020	% tree-ring sites burned 1985–2020
Chiricahua	17	5	5	100.0
Jemez	100	25	19	55.0
Kaibab	8	10	14	100.0
Pinaleño	11	13	3	84.6
Rincon	60	25	18	70.0
Santa Catalina	30	13	5	96.7
Other	180	0	38	23.9
All	406	91	102	50.7

plots. Those with high burn severity as measured by CBI generally showed high tree mortality (Fig. 3). Overall, 14.9% of plots were devoid of live trees of any size, and 31.1% had no live overstory trees. These areas were often characterized by high dead and down fuel loads, especially in larger size classes, from the fire-killed forest. We observed that modern fires at many sites had completely consumed fire-scarred material sampled by earlier researchers. At the low end of the severity gradient, plots contained intact tree canopies of mixed size- and age-classes, often displaying relatively light fuel loads, particularly on the Kaibab Plateau and in the Rincon Mountains, where prescribed burning has been most consistently utilized through time[47,48,54,55].

To compare contemporary fire severity with the historical, low-severity fires that scarred but did not kill fire-recording trees, we developed a logistic regression model predicting tree mortality from contemporary satellite-measured CBI. Our model (Supplementary Fig. 3) identified the 0.5 probability of overstory tree mortality (mortality more likely than not) at a modeled CBI threshold of 1.61. This value aligns closely with the 1.73 CBI threshold of 0.5 probability of ponderosa pine tree mortality in the Forest Inventory and Analysis data (FIA)[56] from Arizona and New Mexico identified by Woolman et al.[57]. Applying our 1.61 CBI threshold, 42.4% of the 206 sites that burned in the contemporary period had first-entry fires in which overstory tree mortality was more likely than not. First-entry fire refers to the first known occurrence of any type of fire following a period of fire exclusion[19].

We assessed relationships between fire management strategy and contemporary burn severity, finding that 14.8% of sites in wildland fire use, 15.4% in prescribed burns, and 53.4% of sites in suppressed wildfires burned at severity levels exceeding 1.61 CBI (Fig. 4). In wildland fire use and prescribed burns, fire history sites burned significantly less severely than those burned in suppressed wildfires (−0.9 and −0.8 units of CBI, respectively, linear mixed-effects model $p < 0.001$, $N = 302$). Proportion of sites burning above the threshold for likely tree mortality varied by geographic area, from 0% on the Kaibab Plateau to 73.1% in the Santa Catalina Mountains (Table 1). In contrast with the first contemporary fire, 35.7% of sites burned by second-entry fires and 0% of sites burned by third-entry fires exceeded the likely mortality threshold (these included areas that sustained live trees but also treeless areas where canopy trees had been entirely killed by the first contemporary fire).

Discussion

In this study, we brought together two spatially extensive, long-term datasets to quantify fire regime changes over the last three centuries in dry conifer forests in the southwestern US. At hundreds of tree-ring fire history sites, fire regimes were historically dominated by frequent and low-severity fires that effectively ended in the late 1800s. While the collapse of this fire regime and resulting change to forests is well documented[15,16,18], the extent to which recent increases in fire activity might fall within historical norms has not previously been rigorously analyzed. Here, we show that contemporary patterns of burning in dry conifer forests bear little resemblance to historical fire regimes in two important ways. First, despite rapid increases in fire activity observed over the last several decades[22,53], fires are still burning far less frequently now than they were historically. Second, trees in this forest type historically survived many fires over centuries, but recent fires are anomalously lethal.

Although recent climate-driven increases in fire activity[21] are evident across our study area, our findings highlight that fire is still very infrequent relative to historical norms. Based on 10-year moving averages of fires per decade, fire since 1985 is over 80% less common than it was historically, with fires burning at a rate of 0.17 per decade in the twenty-first century vs. 0.87 per decade over most of the eighteenth and nineteenth centuries. Many studies have demonstrated major decreases in modern fire frequency relative to historical ranges of variability in fire-adapted forests of the western US[58,59]. The causes of the decline in fire, including the removal of fine fuels following the onset of livestock grazing, cessation of Indigenous burning, and later direct fire suppression, are well understood[60,61]. Historical fire regimes across our study area effectively ended in the late nineteenth century. Contemporary fire occurrence is approaching historical norms in some areas, with 15% of sites burning as frequently or more frequently than historically (though burn severity at these sites may be more severe, as described below). Notably, the return of fire occurred relatively early in the Rincon Mountains in southern Arizona, where progressive fire management was initiated in the 1970s[47]. Still, most sites are burning far less often than historically: as of 2020, half of our fire history sites had yet to burn in the contemporary period, attesting to a still growing fire deficit[19,62].

At fire history sites where fire has returned, contemporary burn severity is substantially higher than that recorded in the tree-ring record. Of tree-ring fire-scar sites that burned, nearly half (42%) experienced fire effects that are more likely than not to be lethal to mature trees. Though such events may have occurred occasionally in some dry conifer forest locations over the historical period, they cannot have been as common or extensive as they are now. Fire history sites survived and recorded an average of 14.2 fires historically and individual trees recorded on average 6.6 fires. If these fires burned at moderate to high severities (CBI > 1.61), trees would have a 50% probability of mortality in each fire, and the chance that a tree at such a site would survive more than six fires is less than 1% ($0.5^{6.6} = 0.01$). Increased severity and tree mortality is expected to be associated with increased heat released by fires burning abundant fuels under warm and dry conditions but may also be imparted by elevated pre-fire tree drought stress in dense stands and a warmer, drier climate[63]. While our samples are at the scale of fire history sites <5-25 acres in size, patterns of historical burning recorded across networks of these sites has been shown to be broadly representative of large dry conifer forest landscapes 250-25,000 acres[47,64] across the region[18], and many of the contemporary fires that burned over these sites exceeded 25,000 acres. Accordingly, our empirical assessment that contemporary severity is higher than historical norms at fire history sites is indicative of changes occurring regionally across dry conifer forest landscapes. These findings add to a growing body of work conducted across a wide range of spatial and temporal scales demonstrating that contemporary fires burning in southwestern forests have become more severe, not just in recent decades, but also in sharp contrast to events over recent centuries or longer[25,65–68].

Sites burned in suppressed wildfires exhibited higher severity than those burned in other fire types, likely related to the conditions under which those different fire types were burning, with prescribed and wildland fire use fires occurring under less extreme fire weather. Both prescribed burns and wildfires managed for resource benefit have been shown to moderate the severity of subsequent wildfires and sustain dry forest ecosystem function[65–70]. Second-entry fires also burned less severely than the first contemporary wildfire in our study, in accord with the findings of prior research[71–74].

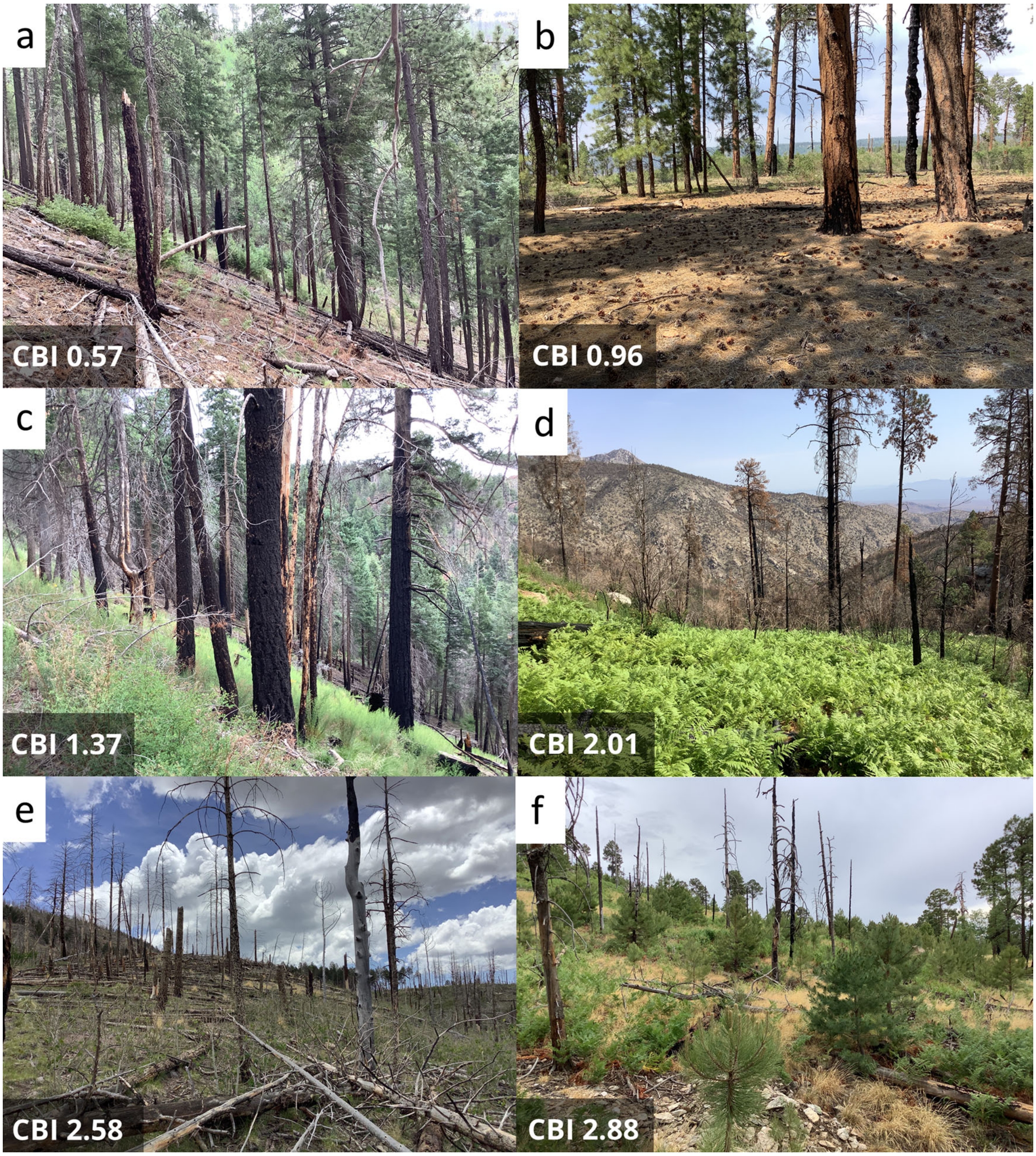

Fig. 3 | Contemporary fire effects at fire history sites that historically recorded low-severity fire. Plot photographs illustrate the spectrum of burn severity in six field-sampled geographic areas: **a** Chiricahua, **b** Kaibab, **c** Pinaleño, **d** Santa Catalina, **e** Jemez, and **f** Rincon Mountains. The satellite-derived burn severity rating for each of these sites, in units of modeled Composite Burn Index (CBI), which scales from 0 (low-severity) to 3 (high-severity), is given in the bottom left corner. Photograph credit: E. McClure, S. Parks, & M. Kunkel.

Conclusions and management implications

Our results clearly demonstrate that hundreds of fire history sites which burned frequently at low severity for centuries are now burning far less often and more severely than they did historically. Consequently, our findings add to a growing body of evidence that contemporary fire regimes in southwestern dry conifer forests are substantially departed from historical norms[36,64]. Our findings are in direct contrast to the assertion that burning patterns today are within the range of variability that occurred prior to Euro-American colonization[34,35], an assertion that has been largely invalidated due to methodological inaccuracies and unsupported logical inferences[36,39,43].

Land management agencies such as the US Forest Service and the National Park Service aim to protect communities from wildfire and improve resilience to inevitable fire[75], which can be accomplished, at least in part, by promoting fire regimes more characteristic of historical norms. Our findings show that prescribed burning and managed wildfire, burning under moderate climatic and weather conditions, result in fire effects that are more aligned with historical fire regime characteristics (i.e., low-severity fire). Our findings therefore support abundant previous research that has demonstrated how prescribed burning and managed wildfire can achieve stated objectives[76], restore historical forest structure[77], and increase forest resilience to future fire[78–80]. Where the risks of severe fire are particularly high (e.g., in the wildland urban interface or watersheds that provide critical surface water supplies), antecedent thinning and fuels reduction treatments are often necessary prior to the restoration of low-severity fire[20,73,81]. In any case, intentional and informed management strategies are essential to protecting communities and improving forest resilience, particularly in forest ecosystems with markedly altered structure, function, and disturbance regimes[43]. Restoration of Indigenous fire stewardship and integration of diverse stakeholder collaboration also offer promising paths forward to expanding the ecological and social benefits of fire in sustaining ecosystem values[43,77,82–84].

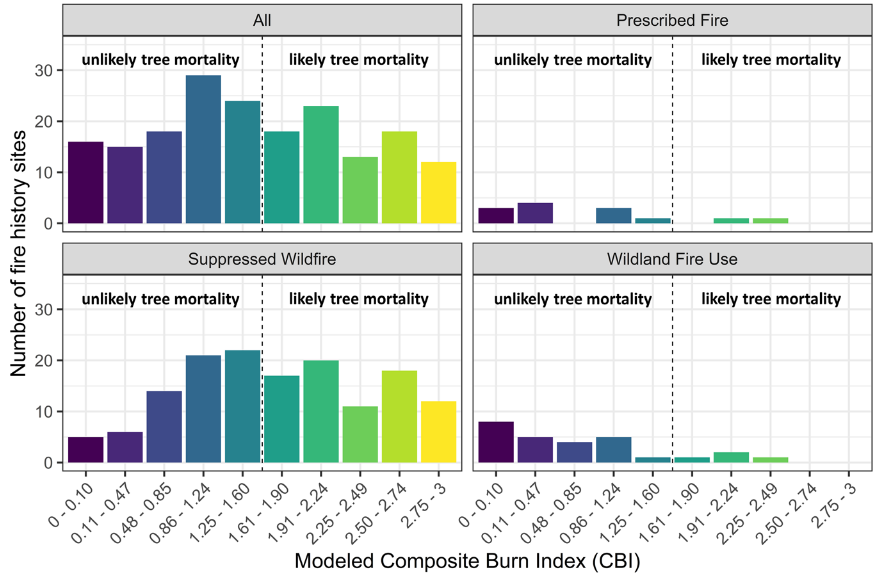

Fig. 4 | Burn severity, quantified by modeled Composite Burn Index (CBI), for the first fire between 1985 and 2020 at tree-ring fire history sites in the southwestern United States. Burn severity is reported for all fire types, prescribed burns, suppressed wildfires, and wildland fire use. The latter is defined as any wildfire not managed under a full suppression strategy. Sites were filtered by our ability to assign fire type and CBI value: $n = 186$ for all, 13 for prescribed burn, 146 for suppressed wildfire, and 27 for wildland fire use. Divisions correspond to standard CBI severity classes (Key and Benson[93]) subdivided by thirds. The dashed line represents a CBI value of 1.61, corresponding to the threshold above which the probability of overstory tree mortality exceeds 50% (mortality more likely than not).

Materials and methods

Study area

Our southwestern US study area comprises the states of Arizona and New Mexico (Fig. 1). We focused on these states because of the recent increase in high-severity fire in this region[24,26] and the availability of extensive tree-ring fire-scar records available through the North American tree-ring fire-scar network v1.1 (NAFSN)[40]. The climate of the study area is semi-arid, with bimodal precipitation peaking in winter (December to February) and during the summer monsoons (July to September), when portions of the region can receive >50% of their annual precipitation[85]. Fire history sites used in this study range from 1552 to 3105 meters (~5000 to >10,000 feet) elevation. Dry forests are dominated by ponderosa pine and Douglas-fir and may also contain Arizona pine (*Pinus arizonica*), Southwestern white pine (*Pinus strobiformis*), white fir (*Abies concolor*), quaking aspen (*Populus tremuloides*), and oak (*Quercus gambelii*), and rarely, Engelmann spruce (*Picea engelmannii)*, limber pine (*Pinus flexilis*), piñon pine (*Pinus edulis*), and juniper (*Juniperus deppeana* and *J. scopulorum*).

Historical fire records

At the time of our analysis (2021), the NAFSN contained 2562 fire-scar sites, including 600 in Arizona and New Mexico[86]. Of the 600 sites, tree-level fire-scar data with sufficient sample size (at least three trees, recording at least four fires between 1700–1880) were available for 406 sites, which we refer to hereafter as our fire history sites (Fig. 1 and Supplementary Table 1). To generate a single composite time series of fire occurrence at each site, we used the burnr package (v. 0.6.1)[87] in the R statistical platform (v. 4.1.3)[88], applying filters for minimum number of trees recording (two), minimum number of trees scarred (two), and proportion of trees scarred (0.10).

Comparisons of tree-ring reconstructed fire regimes with mapped modern fires in the same landscape indicate that the point records from fire-scar records accurately represent the spreading process of landscape fire in dry conifer forests[47]. In addition, gridded, non-targeted, and census sampling designs of fire-scarred trees all provide similar results, confirming that fire-scar sites are representative of frequent, low-severity fire that was widespread in dry conifer forests of the region[45–51].

Contemporary fire records

We obtained fire perimeters from the Monitoring Trends in Burn Severity (MTBS) program[52,89], which includes all fires over 1000 acres (405 ha) in our southwestern study area occurring from 1985 to 2019. To capture fires with acreage less than 1000 and/or occurring in 2020, we acquired fire perimeters from the National Interagency Fire Center (NIFC)[90]. We intersected these fires with fire history site locations (Fig. 1), identifying 102 contemporary fires intersecting 206 of 406 fire history sites. Fires ranged in size from 25 to over 538,000 acres.

For each fire, we generated a gridded burn severity map, represented as modeled Composite Burn Index (CBI), using Google Earth Engine[91] and code developed and distributed by Parks et al.[92]. CBI, which scales from 0 to 3, was developed as a field protocol for validating satellite-derived burn severity 1 year after fire[93], and can be modeled from satellite data[92]. We used modeled CBI as opposed to delta Normalized Burn Ratio (dNBR)[10,11], to improve comparability across fires, sites, and years[92]. Satellite-measured CBI better predicts overstory ponderosa pine tree mortality in the southwestern US than dNBR[53]. Subsequently, we extracted CBI values at each fire history site for each overlapping recent burn. For any sites which experienced more than one fire in the contemporary timeframe, we considered only the first-entry fire.

Field sampling

To quantify tree mortality from contemporary fires, we sampled fire effects at 74 of the 406 fire history sites used in the study. We located the field sites across a gradient of contemporary burn severity and fire management strategies. For example, proportion of fires in the full suppression category ranged from 100% in the Pinaleño and Santa Catalina Mountains to 14% on the Kaibab Plateau. Similarly, the proportion of sites which burned with high probability of tree mortality (CBI > 1.61) ranged from 73% in the Santa Catalina Mountains to 0% on the Kaibab. Data collection focused on six key geographic areas (Fig. 1 and Table 1) where networks of fire history sites had been established prior to wildfires occurring over the previous 10 years (2011–2020): the Jemez[45,94–96], Rincon[47,97], Santa Catalina[98], Pinaleño[51], and Chiricahua Mountains[49,99–104], and the Kaibab Plateau[54,55]. In the Jemez Mountains, sites are in Bandelier National Monument (including the Bandelier Wilderness), the Valles Caldera National Preserve, and the Santa Fe National Forest. The Rincon Mountain sites are mostly located in the Saguaro Wilderness (within Saguaro National Park), and about half of the sites on the Kaibab Plateau are in proposed wilderness in Grand Canyon National Park; the remaining sites sampled in Arizona are within the Coronado and Kaibab National Forests.

We relocated each fire history site and established a 10-m radius plot. If we found a tree or stump sampled in the original fire history data collection, the plot was centered at its location (see Supplementary Fig. 2); if a sampled tree was not located (typically due to high-severity fire effects), we centered the plot at the coordinates provided by the original researcher. Where we found multiple sampled trees or stumps at least 20 m apart, we installed a plot at each, for a total of 91 plots at 74 distinct fire history sites. For all trees in the field plots, we recorded diameter at breast height (dbh), species, and status (live or dead). We measured diameter and assigned species for downed logs and recorded an overall count of trees both live and dead, standing and down. A qualitative description of site conditions and photographic documentation (Fig. 3 and Supplementary Fig. 2) completed our site characterization.

Data analysis

Our first objective was to compare historical and contemporary fire frequency. Although some fire history sites recorded fires in the 1400s and earlier, a consistent record across all sites was not interpretable until around 1700. To generate a continuous time series of fire occurrence from both the site composites generated from site-level fire history data and contemporary fire dates from MTBS and NIFC, we cut off the dendroecological record at the year 1984, from which point (1985–2020) we appended the modern, satellite-derived fire record. Because the contemporary period was only 35 years and included relatively few fires (and even fewer reburns necessary to produce fire intervals) compared with 180 years for the historical period (1700–1880), a direct comparison of mean fire return interval at individual fire history sites was infeasible. Instead, we calculated 10-year moving averages of fires at each site from 1700 through 2020, which we used to examine fire frequency trends across the entire time frame of our study.

Our second objective was to compare historical and contemporary fire severity. To compare fire effects derived from two distinct types of evidence (tree-ring fire scars and satellites), we classified contemporary severity (modeled CBI) as a binary categorical variable related to mature tree mortality vs. survival, as follows: (1) unlikely tree mortality; consistent with a tree surviving to record fire scars, and (2) likely tree mortality, wherein trees are killed and thus would not record fire. Our implicit assumption is that historically, for living trees to have recorded multiple short-interval fires without being killed, those fires must have predominantly burned at a severity unlikely to result in extensive overstory mortality. However, fire severity above this level—with likely overstory mortality—would be inconsistent with historical norms of low-severity fire across dry conifer forests of the southwestern US. These norms were established by a suite of dendroecological studies that evaluated potential biases in sample design and data analyses, all concluding that the fire-scar sites and networks are representative of the broader forests in which they were collected. For example, comparisons of modern tree-ring reconstructed fires with mapped fires in the same landscape indicate that the point records from fire-scars accurately represent the spreading process of landscape fire in dry conifer forests[47]. In addition, gridded, non-targeted, and census sampling designs of fire-scarred trees all provide similar results, confirming that frequent low-severity fire was common, recurrent, and widespread and that fire-scar sites are representative of the broader dry conifer forests[45–51].

To develop the tree mortality classification, we generated a logistic regression model relating CBI to field-measured tree mortality, and used it to identify the CBI threshold above which probability of overstory tree mortality exceeds 0.5—in other words, overstory trees are more likely than not to be killed. Using this 0.5 probability of mortality threshold avoids biasing our contemporary severity classification toward either a more conservative or liberal interpretation of severity.

To generate our 0.5 probability of mortality threshold (Supplementary Fig. 3), we used site-specific modeled CBI to predict field-measured overstory (dbh ≥12.7 cm) tree mortality from 834 trees at 87 plots after filtering for size and our assessment of whether, if dead, they were killed by the most recent fire. Our use of trees ≥12.7-cm or 5-in dbh to model the relationship between burn severity and tree survival is consistent with prior studies[57], but also generally supported by the historical ages at which trees recorded fire scars (and thus demonstrate survival through historical fires), as follows. The median number of years between the pith ring (center) of the tree and the first fire scar across our data ($n = 2215$ trees with pith) was 47 years, which corresponds well with 35 years reported by Brown et al.[105] and 52 years reported by Yocom and Fulé[106]. Given that most fire scar samples are collected at <30 cm above the ground (and dbh is 137 cm above the ground), the years between pith and first fire scar may underestimate tree age by up to 5 years[107], accordingly, we estimate the median tree age at first fire scar in our study to range between 47 and 52 years. Established age-size relationships for ponderosa pine in Arizona ($\text{age} = 10.4^* \text{dbh(cm)}^{0.66}$)[108], the most frequently sampled tree species, yield size estimates of 10–12 cm dbh for 47–52-year-old ponderosa pine trees. Thus, we expect that historical fires were generally not lethal for trees ≥12.7-cm dbh for these trees to have recorded multiple fires over 5–10 decades beginning at ages between 47 and 52 years. By species, trees included in this analysis were 29.1% ponderosa pine, 27.2% Douglas-fir, 14.7% Southwestern white pine, 12.1% white fir, 9.1% Arizona pine, 4.9% quaking aspen, 1.9% Engelmann spruce, and less than 1% of other species. To assess the robustness of our results to the tree dbh cutoff used in this model, we also examined relationships between tree survival and CBI using larger cutoff values of 25.4 and 38.1 cm (Supplementary Table 2). We present both the satellite-derived modeled CBI values of contemporary fires as well as the number of fires occurring above or below the tree mortality threshold.

To assess relationships between contemporary burn severity and management strategy, we classified fires by management type (suppressed wildfire, wildland fire use, and prescribed burn). These categories are determined at the fire level and reflect critical differences in management strategy. Suppressed fires are managed to limit fire size and effects through effective containment and extinguishment. Prescribed fires are the product of deliberate ignitions intended to achieve a wide range of objectives but are generally managed to burn at low severity. For the wildland fire use category, we included wildfires listed as "resource benefit," "prescribed natural fire," or "managed for multiple uses," depending on source and date as these terms were variously applied over the study period to refer to the same general type of fire. Each of these terms reflects that the management intent of the fire was to allow it to burn to achieve ecological objectives, like a prescribed fire originating from an unplanned ignition. We recognize that wildland fire use is an outdated term; however, in the fire management community today, there is not a clear successor to it, so we used it for simplicity. Due to smaller sample sizes, we grouped the prescribed burns and wildland fire use fires together for analysis purposes. We tested for differences in burn severity (modeled CBI) of the first contemporary fire between sites burned in suppressed wildfire (160 sites, 34 fires) vs. wildland fire use (32 sites, 12 fires) and prescribed burn (12 sites, 8 fires) using a linear mixed-effects model with fire management strategy as a fixed effect and fire identity as a random effect using the package glmmTMB[109]. All analyses and data visualization were performed in R (v. 4.1.3)[88].

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Tree-ring fire-scar data are available from the IMPD or from the contributor listed in Supplementary Table 1. The fire perimeters were obtained from the Monitoring Trends in Burn Severity Program[10,89] and the National Interagency Fire Center[90]. Field data are available in a Dryad repository (https://doi.org/10.5061/dryad.98sf7m0sn).

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Competing interests
The authors declare no competing interests.

Additional information

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