Pyrogeography of extraordinary wildfires

Calum X Cunningham[1†], Grant J Williamson[1], John T Abatzoglou[2], Crystal A Kolden[2], Matthew W Jones[3], Michael Fromm[4], David A Peterson[5], Fantina Tedim[6], Mike Flannigan[7], Fay H Johnston[8], Nicolas Borchers-Arriagada[8], David MJS Bowman[1]

[1] Fire Centre, School of Natural Sciences, University of Tasmania, Hobart, Australia

[2] Department of Management of Complex Systems, University of California, Merced, Merced, CA, USA

[3] Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia (UEA), Norwich, UK.

[4] Naval Research Laboratory, Washington D.C., USA.

[5] Naval Research Laboratory, Monterey, CA, USA.

[6] Centre of Studies in Geography and Spatial Planning (CEGOT), Faculty of Arts and Humanities, University of Porto, Porto, Portugal.

[7] Department of Natural Resource Science, Faculty of Science, Thompson Rivers University, Kamloops, British Columbia, Canada.

[8] Menzies Institute for Medical Research, University of Tasmania, Hobart, TAS 7000, Australia

[†]calum.cunningham@utas.edu.au

Article type: Review

This is a non-peer reviewed preprint submitted to *EarthArXiv*

Abstract

Extraordinary wildfires – defined by anomalous fire behaviour, physical attributes, paleo-ecological context, spatiotemporal scales, or consequences – have emerged as defining features of the global wildfire crisis. Extraordinary wildfires have profound impacts on ecosystems, climate, air quality, and human societies. In this Review, we characterise key dimensions of extraordinary wildfires, contextualise their global distribution and trends, and review causes and consequences. Globally extraordinary fires (highly anomalous in ≥1 dimension) show distinct geographic patterns, being most common in boreal and temperate conifer forests, Mediterranean systems, and deserts, but less so in tropical and subtropical forests and savannas. Upward trajectories in the 21st century are most pronounced in boreal forests and temperate conifer forests. Drought and fire weather are tightly linked to extraordinary fires in cool, moist or fuel-rich extratropical biomes, but weakly associated in deserts, grasslands and savannas. Other additional drivers and amplifiers of extraordinary fires include invasive plants, interruption of Indigenous burning regimes, vegetation mismanagement, and an expanding wildland interface. The primacy of climate and fire

weather – which are exacerbated by anthropogenic climate change – highlights the urgency with which we must adapt management of anthropogenic and natural environments in the face of a more fire-prone future.

1. Introduction

Extraordinary wildfire events are emerging as defining features of the 21st-century fire crisis[1]. The last decade has seen a surge of highly consequential fires, from vast forest fires that caused extraordinary emissions and ecological damage[2-4] to wildland-urban disasters that claimed many lives and buildings[5-9]. Much of the concern about a wildfire crisis stems from coalescing societal and scientific realisations that wildfires are becoming more extraordinary in terms of fire behaviours, economic and environmental impacts, and temporal and geographic scales. Yet, precisely quantifying the magnitude, rate and geographic scale of extraordinary wildfires remains elusive, with little agreement on their definition or dimensions.

Although wildfires are increasingly described as "mega", extreme, unprecedented, or extraordinary[3,4,10-16], defining them as extraordinary is not straightforward due to their multidimensional nature[17]. Fires may be extraordinary due to their size[18], energy[19], rate of spread[20], socioeconomic destructiveness[5-9,21], plume behaviour[22], temporal nature[23], and emissions[24,25] among other characteristics – though not necessarily all at once. While extraordinary wildfires have occurred throughout history – such as ancient Australian Aboriginal Dreamtime accounts of major conflagrations[26], and disasters that claimed over 1,000 lives (Peshtigo, USA, 1871; Kursha-2, Russia, 1936) – the consequences and visibility of today's extreme fires, now tracked by satellites and amplified by the media[27], raise critical questions about where and in what way fires are becoming more extraordinary.

Despite increasing attention[11,12,28], there is no single definition of what makes a wildfire extraordinary. This is partly driven by the fact that unlike some other natural hazards such as earthquakes, the multidimensionality of wildfires means there is no single measurement or "scale of gravity" (sensu Tedim, et al. [11]). This multidimensionality highlights the need to consider extraordinary wildfires through a flexible multi-dimensional lens. This Review focuses primarily on the definition, geographic patterns, and trends of extraordinary fires, while also briefly outlining the principal causes and consequences linked to recent extraordinary events. We conclude by outlining the pressing knowledge gaps and priorities for research and adaptation.

2. Operating definition of extraordinary wildfires

Characterising and quantifying extraordinary wildfires is complicated by the varied definitions and metrics available to describe fire. Numerous frameworks have sought to define what makes a wildfire "extreme" or "extraordinary," variously focusing on physical fire behaviour, attributes, or impact.

2.1 Defining extraordinary wildfires

In the most widely used classification of "extreme" fire events, Tedim, et al. [11] highlight a sprawling array of terms and thresholds used in the literature. They proposed a 7-category system for classifying extreme wildfire events, later extended to extreme seasons (Box 1) by Duane, et al. [29], based on real-time observable fire behaviour: fireline intensity (kW m^{-1}), rate of spread (m s^{-1}), fireline length (m), downdrafts, spotting activity, spotting distance (m), and formation of pyrocumulonimbus (pyroCb) firestorms. Notably, that classification framework excluded post-fire metrics such as *fire size* and *socioeconomic impacts,* instead focussing on real-time observable variables most relevant to suppression operations. But for other applications – such as global distribution mapping or trend analysis – a broader set of metrics are required, which need not be available in real time.

In parallel to formal classification systems, related terms have gained traction in both public and scientific discourse. Most prominent is the growing, though inconsistent, use of "megafire" to describe fires that are extreme in size, behaviour, resistance to control, novelty, severity, socioeconomic impacts and environmental impacts[18]. Despite the varied usage, Linley et al. [18,30] argue that megafire should be standardized to refer to fire size (>10,000 ha), which points to absolute *fire size* as a widely recognised axis of extraordinary fire.

In addition to physical attributes, fires have been described as extraordinary by virtue of their impacts on societies, ecosystems, or the atmosphere. "Extraordinary events"[12] and "events that matter"[28] have been framed as the outcomes of interacting social and biophysical extremes – highlighting, for example, how extreme social exposure can precondition average fire events to have extreme consequences[12].

Integrating physical and socioeconomic dimensions, as well as quantitative and qualitive evidence, the State of Wildfires project[17] adopted a broad, dual-track framework for identifying "extreme" wildfires as those that are statistically anomalous or that experts judged to have had exceptional ecological or societal impacts within their regional context. This approach allows episodes of wildfire to be flagged as extraordinary within regional contexts even if they do not surpass globally defined thresholds in observable fire properties. Both regional and global approaches to describing extraordinary fires have merit, depending on the application.

Extreme events are often delineated using thresholds, yet such thresholds themselves are rarely clear-cut. Some dimensions, such as pyroCbs, are naturally categorised as binary extraordinary events, but for most continuous dimensions, "extreme" often refers to the tail of the distribution; examples include daily energy in the top 0.01-0.003%[19,31] and the largest 1% of fires[32]. Extreme fire size, in particular, has been applied inconsistently, with area-based thresholds varying by multiple orders of magnitude depending on geographical, ecological, and historical contexts[11]. In addition to arbitrariness, statistical thresholds also imply a relationship to a baseline. Determining such natural baselines is plagued by a raft of uncertainties relating to short record lengths and shifting fire regimes. Nevertheless, while thresholds themselves are often arbitrary, they remain useful tools for contextualising extraordinary fires – as long as users clearly report them and how they relate to a given objective.

Here, we offer an operating definition of extraordinary fires as:

> *those that are extremely anomalous in one or more of the key dimensions that capture wildfire behaviour, spatiotemporal attributes, paleoecological context, geographic location, and socioecological effects* (Table 1 and Fig 1).

ETo illustrate how some of these dimensions manifest in practice, Figure 1 characterises the multidimensional nature of a collection of fire events that were unambiguously extraordinary, albeit in different ways. The 2024 fire disaster in Valparaiso (Chile) was fast-moving and highly energetic, leading to the tragic loss of at least 133 lives[7] and 14,000 structures[17]. Similarly, the Lahaina fire (USA, 2023), despite being relatively small (850 ha) and short-lived[33], was extremely fast-moving, lethal (102 deaths)[34] and damaging (~2200 buildings)[33]. In contrast to devastating effects on human life and property, the 2020 fires in the Pantanal wetlands of central South America caused staggering ecological damage, burning one third of the world's largest tropical wetland and killing an estimated 17 million vertebrates[35-37]. The Gosper's Mountain[38] (Australia, 2019/20; 512,000 ha) and Fort McMurray[6] (Canada, 2016; 590,000 ha) fires were both exceptionally large, burned for >2 months, involved multiple pyrocumulonimbus firestorms[39], but only the Fort McMurray fire, due to its location, caused major property destruction. Highlighting regional context-dependency, the area burned by the Evros Fire (Greece, 2023) – famed as the largest in European Union history – was only ~11% of a 2025 fire that burned ~800,000 ha in Etosha National Park (Namibia) in just ~1 week[40]. The varied qualities of the fires in this non-systematic collection highlight how fires can be extraordinary in different ways.

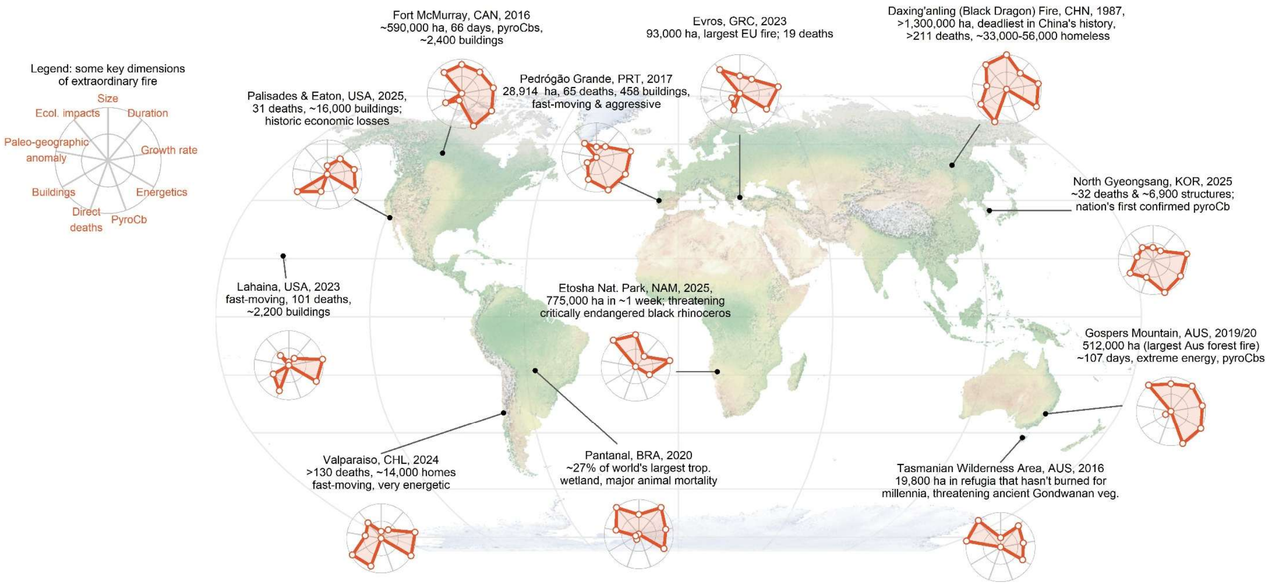


Figure 1. Wildfires can be extraordinary in numerous ways. *Events are a non-systematic selection of fires considered to be extraordinary in different ways. Axes are based qualitatively on accounts of the fires and should be considered conceptual. These axes reflect only a portion of the ways in which fires can be extraordinary.*

Box 1 | Extraordinary fire events, extraordinary fire seasons, and smoke

Extraordinary wildfires are singular episodes—events that stand out through their attributes or impacts. By contrast, **extraordinary fire seasons** (or fire years)[32] represent cumulative extremes: periods in which widespread, synchronous burning produces anomalous outcomes, such as total area burned or total emissions. These seasons arise when regional climatic anomalies, such as long-term drought, sustain high fire danger across broad landscapes[2-4]. Extraordinary seasons often consist of numerous extraordinary fires that together overwhelm regional resilience.

Smoke provides a vivid illustration of this distinction. While some individual fires generate dense local plumes, the most extreme smoke concentrations – especially in the tropics – usually emerge from extraordinary fire seasons, when hundreds or thousands of fires collectively degrade air quality across entire regions for periods of weeks to months. For example, the prolonged 1997 and 2015 Indonesian peat fires – ignited by agricultural burning practices and sustained by El Niño-driven drought – produced sustained regional haze that affected tens of millions of people across Southeast Asia[41,42]. These seasons caused hundreds of thousands of premature deaths in Southeast Asia[42], with El Niño associated with ~8-fold more deaths than La Niña in the region[41].

Because smoke is highly dynamic in space and time – capable of travelling long distances and persisting well after fires have extinguished – it is difficult to attribute it to a single event or specific fire perimeters. Nevertheless, extraordinary smoke events are undeniably among the most significant effects of fire on humans.

Table 1. Key dimensions of extraordinary fire events. The table outlines some notable dimensions that can be used to describe extraordinary fires by virtue of behaviour, attributes, or impacts.

DIMENSION ***(DOMAIN)***	**DEFINITION & IMPLICATIONS**
Intensity *(Energy)*	The *rate* of energy (also known as power) released over different stages of combustion[43]. Often quantified by fireline intensity (kW m^{-1}) or reaction intensity (kW m^{-2})[43], or indexed by fire radiative power (FRP). *Implications: Pivotal role in the controllability of fire[44].*
Radiative Energy *(Energy)*	Fire radiative energy is the integration of *power* over space and time (J m^{-2}). It can therefore be estimated by integrating FRP over a fire's duration and extent[45]. *Implications: Scales closely to biomass burned and emissions[46].*
Pyrocumulonimbus *(Energy, weather)*	Coupling of fire behaviour and weather, leading to intense thunderstorms above highly energetic wildfires. PyroCbs are driven by extreme heat and convection from the fire, and can generate their own weather including strong winds, tornadoes, and lightning, which can ignite new fires[22,47]. *Implications: Exacerbate fire spread and behaviour, and inject smoke and aerosols high into the stratosphere[22], potentially affecting the climate.*
Size *(Space)*	The area burned by an individual fire, usually measured in ha or km^2. *Implications: Extremely large fires reduce pyrodiversity, impairing biodiversity[48,49]. Fire management effort and costs can increase with fire size.*
Spotting *(Space)*	The ignition of new fires downwind of the fire front caused by embers and firebrands[11]. *Implications: Leads to accelerated growth and new spot fires[50] that have been documented up to ~33 km ahead of the main fire front[51]. Ember transport is one of the key ways that fires enter built communities. Long-distance spotting may limit the efficacy of fuel treatments.*
Growth Rate *(Space-time)*	The rate at which a fire expands, often measured in ha $hour^{-1}$ or km^2 d^{-1}. *Implications: Influences evacuation and suppression, and therefore structure losses; e.g., In the USA, fast-growing fires are associated with house loss[20].*
Rate Of Spread *(Space-time)*	Speed at which the leading edge of the fire moves, often measured in m s^{-1} or km h^{-1}. *Implications: Like growth rate, rate of spread influences suppression and evacuation.*
Duration *(Time)*	The duration a wildfire burns, from ignition to extinguishment. Because peat fires can smoulder for many years, duration measured by satellites is often considered flaming combustion. *Implications: Long-lived fires cause prolonged smoke exposure and occupy suppression resources.*
Nocturnal fire *(Time)*	Burning aggressively overnight, when fire intensity and growth rate typically subsides[23,52]. *Implications: Complicates firefighting because night traditionally affords respite to firefighters[23].*
Seasonal novelty *(Time)*	Burning aggressively at unusual times of the year, such as outside of typical fire seasons. *Implications: Challenges for firefighting, such as international resource sharing. Ecological implications for the timing of species phenology (e.g., reproduction, establishment).*
Paleoecological novelty *(Deep time)*	Occur in locations that, on a paleo-ecological timescale, rarely experience fire. *Implications: In places and ecosystems not adapted to fire, potentially leads to regime shifts, e.g., fire in Gondwanan refugia that has rarely experienced fire over millennia[53-55].*
Severity *(Effects)*	Describes effects on ecosystems, often referring to the loss or decomposition of organic matter by fire, though there is no single defintion[43]. *Implications: Provides a measure or index of ecological destruction and impacts.*
Fire smoke *(Effects)*	Fine aerosolised particles, typically measured using emissions (megatonnes) or concentrations (µg m^{-3}) of very small particles ≤ 2.5 µm, known as $PM_{2.5}$. *Implications: Tiny particles penetrate deep into the lungs and bloodstream, causing widespread health effects. $PM_{2.5}$ exposure is linked to hundreds of thousands to millions of premature deaths per year[41,56].*
Carbon emissions (*Effects*)	Greenhouse gas emissions measured as megatonnes of carbon dioxide equivalent (eCO2). *Implications: Global climate system feedbacks[57].*
Socioeconomic consequences *(Effects)*	The effect of fire on people. Common measures include fatalities, structure losses, direct and indirect economic losses, and evacuations; often referred to as *disasters* or *catastrophes*[27,31,58]. *Implications: Major social and economic ramifications, such as collapse of insurance markets[59], psychosocial trauma[60], and multi-facetted health burden [61].*

2.2 Tracking extraordinary fires: a tension between incommensurate scales & approaches

Identifying extraordinary fires involves a tension between scales and approaches. Regional case studies that describe extraordinary fires in detail (for example, [62]), including the historical and climatological context, are critical for providing causal insight and deep understanding. Paleo-ecological proxies, such as charcoal in sediments[63,64] and fire scars in tree rings[65,66], can extend records centuries to millennia and inform on the degree of novelty. For example, a study of heat-sensitive luminescence signals of archaeological ceramics, coupled with tree-ring fire histories, revealed that the intensity of a planned burn in a ponderosa pine forest (*Pinus ponderosa*) in New Mexico was without analogue over the previous 900 years[67]. But, although critical, such case studies cannot be scaled up to evaluate global patterns or trends.

To systematically contextualise extraordinary fires globally, we must instead rely on globally consistent data primarily from remote sensing observations and disaster records. These offer systematic and spatially comprehensive coverage, but they suffer from the known shortcomings of remotely sensed data, including regional obscuration from dense cloud cover[68] in the tropics and short record lengths, with satellite observations of fire and burned area spanning only 2-4 decades[69-71] and some national fire perimeter datasets spanning several more[72,73]. This temporal shallowness poses major challenges for determining natural variability and long-term rarity, obscuring events that appear extraordinary only over longer timescales. In Tasmania, Australia, fires that burned refugia of an ancient Gondwanan conifer (*Athrotaxis selaginoides*) appear unremarkable in the satellite record but anomalous in palaeoecological records (Fig 1)[53-55]. Such case studies capture paleoecologically anomalous events that global, shallow-time datasets may miss, but they are unable to determine broader patterns and trends. Case studies and global datasets are therefore incommensurate, but used in concert, they can yield the fullest picture of extraordinary fire.

3. The pyrogeography and dynamics of globally extraordinary wildfires

At a global resolution, only a subset of the many facets of extraordinary wildfires can be systematically tracked using global remote sensing records. This section synthesises geographic hotspots and temporal trends (2003-2024) of discrete wildfire events for six such dimensions: (1) daily energy (indexed by summed daily FRP)[19,31], (2) nighttime fire intensity (night FRP_{mean})[52], (3) pyrocumulonimbus thunderstorms[39], (4) duration (days)[74], (5) daily growth ($km^2\ d^{-1}$)[20], and (6) size (km^2)[74]. Events were considered *globally* extraordinary if they exceeded the global 99.9th percentile in at least one dimension (see Supplementary Text 1 for explanation), except for pyroCbs, which were all considered extraordinary.

3.1 Distribution of extraordinary fire events

Satellite-observed geographic patterns

Globally, the proportion of fire events considered extraordinary in at least one dimension is highest in western and boreal North America, Eurasian boreal forests, the Mediterranean basin, southern South America, southern Africa, and much of southern and arid Australia (Fig 2a). In particular, the boreal forests, temperate conifer forests, Mediterranean vegetation, tundra, and deserts emerge as key biomes where individual fires are disproportionately likely to be extraordinary (Fig 3a). Tropical and subtropical regions and grassland biomes experience extraordinary fires, but they are proportionately less common (using global thresholds; Fig 2 & 3a).

The most concentrated distribution exists for pyrocumulonimbus events (Fig 2b). A global inventory of pyroCbs (n = 911, 2013-2024)[39] shows these events are heavily concentrated outside the tropics, with 48% and 33% occurring in the boreal forest and temperate conifer forest biomes, respectively. When normalised by the total number of fire events per biome, pyroCbs are strongly over-represented in temperate conifer, boreal, and Mediterranean forests—by factors of 86, 40, and 11, respectively (Fig 3a). Conversely, pyroCbs have rarely been observed in the tropics (Fig 2b), where the conditions required for them to occur – unstable atmosphere coupled with extremely energetic fire – are uncommon (Box 2)[39].

Box 2 | Pyrocumulonimbus: the most explosive mode of wildfire behaviour

Pyrocumulonimbus (pyroCb) firestorms represent the most explosive mode of wildfire behaviour. They form when extreme fire energy couples with an unstable atmosphere, allowing a fire's buoyant plume to grow into a deep convective cloud akin to a thunderstorm[22]. As with ordinary cumulonimbus, pyroCbs can generate lightning, downdrafts, erratic winds, and even tornadoes, but critically they are not associated with significant rainfall[22,75]. The key distinction between cumulonimbus and pyroCb is that the fire itself supplies the heat that initiates and sustains the convection.

PyroCb formation is rare because only specific meteorological ingredients align to support it – most commonly in the mid- to high-latitudes[39], where hot, dry, windy, and unstable boundary layers coincide with mid-level moisture and lift[76]. When these conditions occur, atmospheric feedbacks can rapidly escalate fire behaviour. PyroCb-generated lightning can ignite new fires kilometres ahead of the main front[75], accelerating fire growth and creating extraordinary challenges for suppression. A hallmark of pyroCb events is their ability to inject vast quantities of smoke into the upper troposphere or stratosphere via a fire-cloud chimney[22], producing volcanic-scale aerosol layers that can persist for months[47].

Fires that release extreme daily energy and burn extremely intensely overnight occur disproportionately in temperate conifer forest, boreal forest, Mediterranean, tundra, and desert biomes (Fig 3a). In contrast, the fastest growing (60%) and largest (70%) fires are most common in highly flammable (sub)tropical grasslands and savannas, but this allocation reflects a roughly proportionate distribution because this biome hosts ~63% of fire events globally[74] (Fig 3a).

Some types of extraordinary fire tend to co-occur geographically (Fig 3b). At the level of individual fire events, fires are rarely extraordinary in all dimensions (n = 19; crosses in Fig 2a), with about three-quarters of events exceeding the 99.9th percentile in just one dimension. At a broader geographic scale (110 km pixels), certain types co-occur more often, notably (i) pyroCb and daily energy, and (ii) daily growth and fire size (Fig. 3b), suggesting shared drivers.

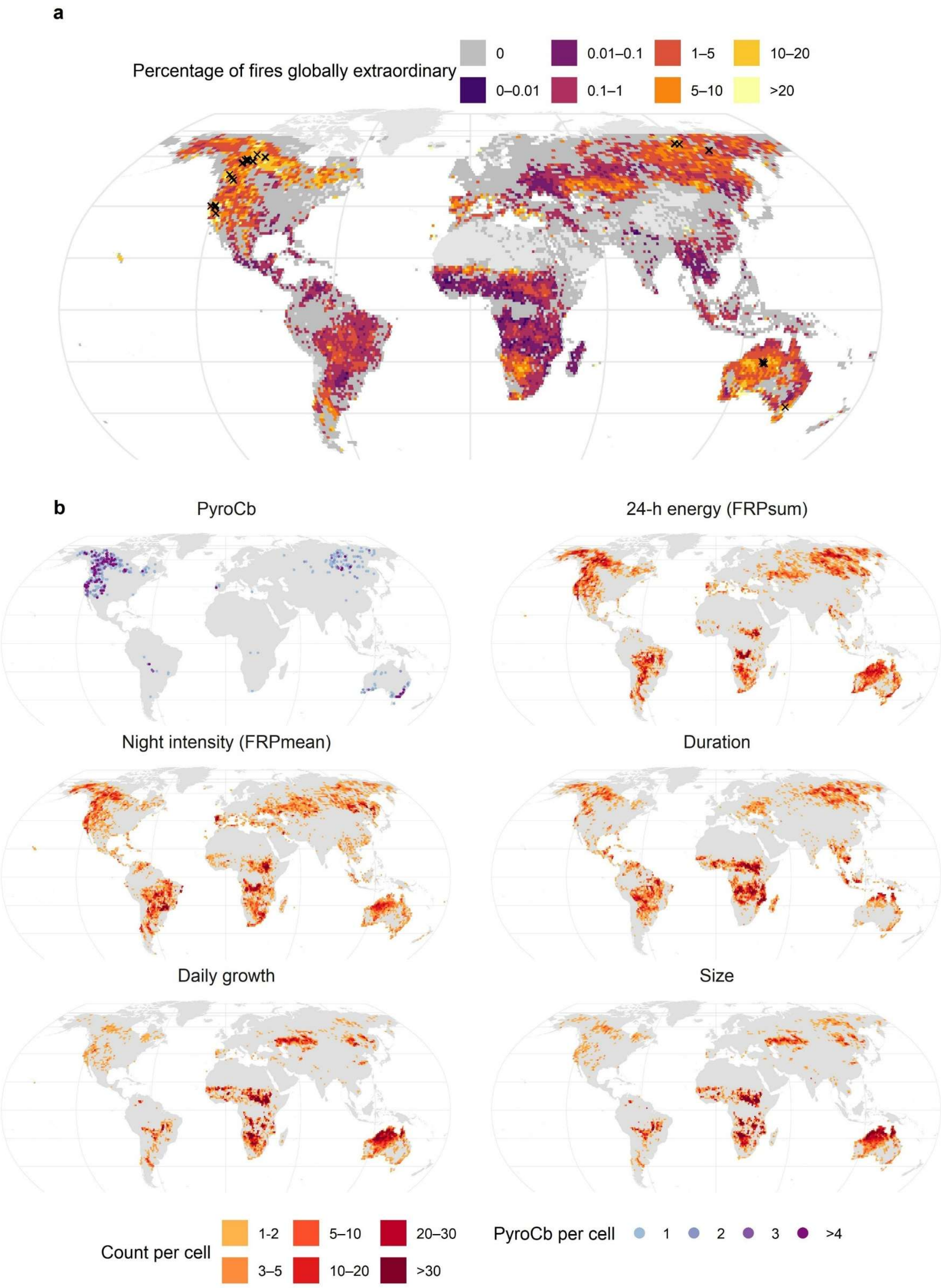


Figure 2. Distribution of extraordinary wildfire events defined by physical attributes of fire. *To summarise the distribution of globally extraordinary wildfires, discrete events in the Global Fire Atlas[74] (2003-2024) were linked to MODIS fire radiative power observations (MCD14ML[69]) and MODIS daily burned area (MCD64A1[70]). Events were considered extraordinary if they exceeded the global* 99.9^{th} *percentile, yielding 19,434 fire events in each dimension (except PyroCbs; N = 911[39]).* ***(a)*** *The percentage of fires globally extraordinary in at least one dimension, summarised in equal-area, equal-shape cells (~110 km resolution). Black crosses (×) show 19 fires that were extraordinary in all six dimensions.* ***(b)*** *The geographic distribution of six dimensions of extraordinary fire, with the* 99.9^{th} *percentile threshold shown in parentheses: pyroCb events (binary), daily energy indexed by summed FRP (7093 MW km*^{2} *d*$^{-1}$*), mean night FRP (117 MW km*^{2}*), duration (34 d), daily growth (68 km*^{2} *d*$^{-1}$*), and size (280 km*^{2}*).*

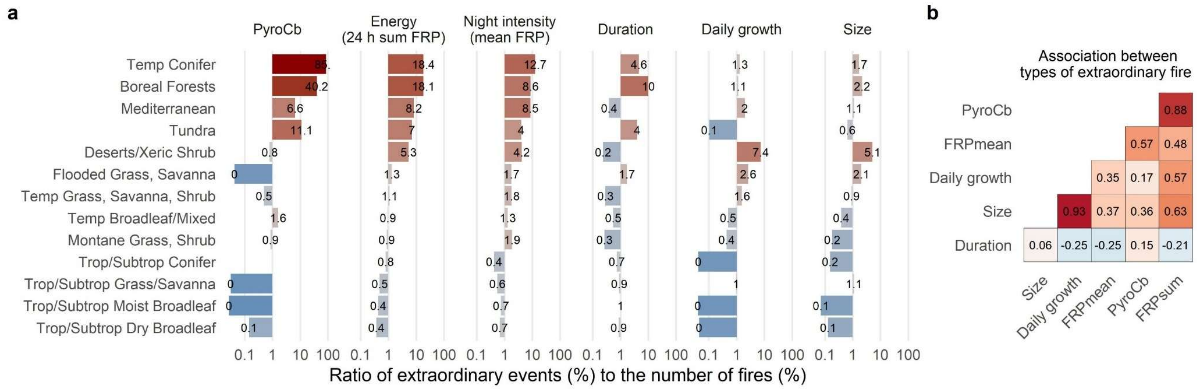


Fig 3. ***Fires differ in their likelihood of being globally extraordinary. (a)*** *The ratio of extraordinary events to fire events, calculated by dividing the percentage of fires considered extraordinary by the percentage of fires in each biome[77] (Fig 2); values above 1 (red) indicate that fires are disproportionately likely to be extraordinary.* ***(b)*** *Heatmap of association (Yule's Q) shows the strength and direction of pairwise correlations between binary indicators of extraordinary fire (Fig 2c).*

Distribution of socioeconomically extraordinary fires

Fires are often described as extraordinary when they have major socio-economic consequences, irrespective of their physical attributes. Fires with extraordinary social consequences – such as major economic losses (for example, top 200 relative to a country's GDP[58]) and major direct fatalities (≥ 10) – disproportionately occur in Mediterranean and temperate forest biomes, where highly energetic fires intersect concentrations of high-value assets[58], noting that social consequences likely suffer more underreporting in developing countries.

Although direct fatalities are among the most confronting consequences of fire, they are far outnumbered by the health effects from smoke exposure[41]. Numerous local and regional studies have estimated the health impacts of specific smoke episodes using combinations of empirical air-quality measurements, remote sensing, meteorology, and statistical modelling [13,78]. Though there are fewer global studies, and despite variations in the magnitude of estimated mortality impacts, all global studies of wildfire-specific $PM_{2.5}$ have shown similar geographic patterns, with large interannual variations and concentrated regional patterns in human exposure[41,56,79-81]. The highest mortality rates attributable to wildfire smoke are clustered in two bioclimatic zones: (1) tropical savanna and rainforest regions, such as sub-Saharan Africa, where up to 70% of total annual exposure to $PM_{2.5}$ is derived from wildfire smoke from seasonal burning[56,80]; (2) temperate and Mediterranean bioregions such as western North America[56]. Importantly, patterns of smoke exposure depend strongly on the timescale considered (Box 1). For example, extreme annual exposure to fire-sourced $PM_{2.5}$ is greatest in the tropics, whereas at shorter timescales, extreme daily $PM_{2.5}$ concentrations can reach comparable levels across both low and high latitudes[79].

Long-duration extreme smoke episodes (≥15 days above 50 µg m^{-3}, 99.9th percentile; Figure S2) exhibit distinct loci in both tropical and extratropical zones (Fig S2). The human consequences of these longer duration extraordinary smoke events vary with the population density in affected regions. For example, Siberia and the northwest of Australia are both very sparsely populated, while millions are affected in other places, such as large cities in the west of the US and Canada, the urban agglomeration of Santa Cruz de la Sierra in Bolivia, and densely populated regions in the Democratic Republic of Congo (Fig S2).

3.2 Trends in extraordinary fires

Satellite-observed trends in key regions and biomes

There is substantial, growing evidence that extraordinary wildfire events have increased in some regions from 2003-2024. Records from the Moderate Resolution Imaging Spectroradiometer (MODIS) indicate that increases are most evident in several fuel-rich forest biomes (Fig 4), where fire weather and fuel moisture limit fire[82,83]. By contrast, decreases are concentrated in grassland regions where fuel loads, rather than fire weather, are the dominant limitation on fire (Fig 4).

Boreal forests are experiencing the most pronounced and consistent increases in extraordinary fires. Upward trends this century are evident for boreal forest fires across the six dimensions evaluated (Fig 4). Emblematic of these trends, Canada's record-breaking 2023 fire season more than doubled the previous burned area record since the beginning of the dataset in 1972[2], with an elevated number of *very large* fires driving most of the total burned area[173]. The 2023 Canadian fire season was followed in 2025 by the nation's second largest burned area on record[84]. In other boreal forest regions such as eastern Siberia, the worst three fire years this century occurred in 2019, 2020, and 2021[85,86], with evidence that intense fires in northern Eurasia are shifting northward[87,88]. Notably, the trend for pyroCbs, despite a short record length (2013-2024[39]), is statistically significant in the boreal forest biome (Fig 3). Canada's 2023 fire season set new records for pyroCb activity, with 142 events representing 84% of the year's global count[39]. Moreover, Siberia's 2024 fire season saw the region's highest number of pyroCbs detected (n = 22) – twice the 2013-2024 average[39].

The temperate conifer forest biome (mostly North America) has similarly experienced increases this century in fires with extreme energy, night intensity, daily growth, and size (Fig 3). Particularly notable is western North America's rise in conditions conducive to overnight fires[23,52], challenging the "active day, quiet night" model of the diel fire cycle and firefighting. Using longer-term national fire perimeter data (1984-2019) in the USA, a distinct change is apparent around the year 2000, in which extreme fires became larger, more common, and more often occurred contemporaneously with other extreme fires[89]. While annual burned area has increased 10-fold in western US forests (1985-2022), the area burned at *high severity* has increased 15-fold[90].

The temperate broadleaf forests of Australia, dominated by *Eucalyptus* species known for their flammability[91], do not exhibit clear trends over the short MODIS record (Fig 4b) but show stronger trends over longer timescales[92]. From 1988-2019, annual burned area in Australia's forests, driven by large fires, has increased linearly while burned area in autumn and winter has increased exponentially[92]. Much of the change appears to have occurred around the year 2000[92]: three of Australia's four years with >1 Mha burned since 1930 occurred after 2000[92]. Although trends in pyroCbs are not yet evident beyond the boreal forests (Fig 4), Australia's 2019/20 Black Summer Bushfires[4] were marked by a 'super outbreak' of them, some of which anomalously persisted into the night[47]. More than half of these pyroCbs injected smoke into the stratosphere, progressively encircling a large swath of the Southern Hemisphere over the ensuing months at a magnitude consistent with major volcanic eruptions[47].

Tropical and subtropical grasslands and savanna show evidence of declining frequencies along five dimensions (Fig 4). This decline fits with a well-documented reduction in burned area this century in African savannas[93], which is likely attributable to cropland expansion[93], with possible roles for precipitation, vegetation greening, and livestock grazing[94,95]. In temperate grasslands, similar declining trends are apparent for extreme daily growth, size, and duration, despite some regional increases in large grassland wildfires (for example, the Great Plains of North America, 1985-2014[96]). In contrast, there has been roughly a doubling in extremely long-duration fires in the typically moist flooded savannah biome (Fig 4). Most illustrative of this trend were extraordinary fires in 2020 and 2024 in the world's largest tropical wetland, the Pantanal wetlands of Brazil, Bolivia, and Paraguay[3,97].

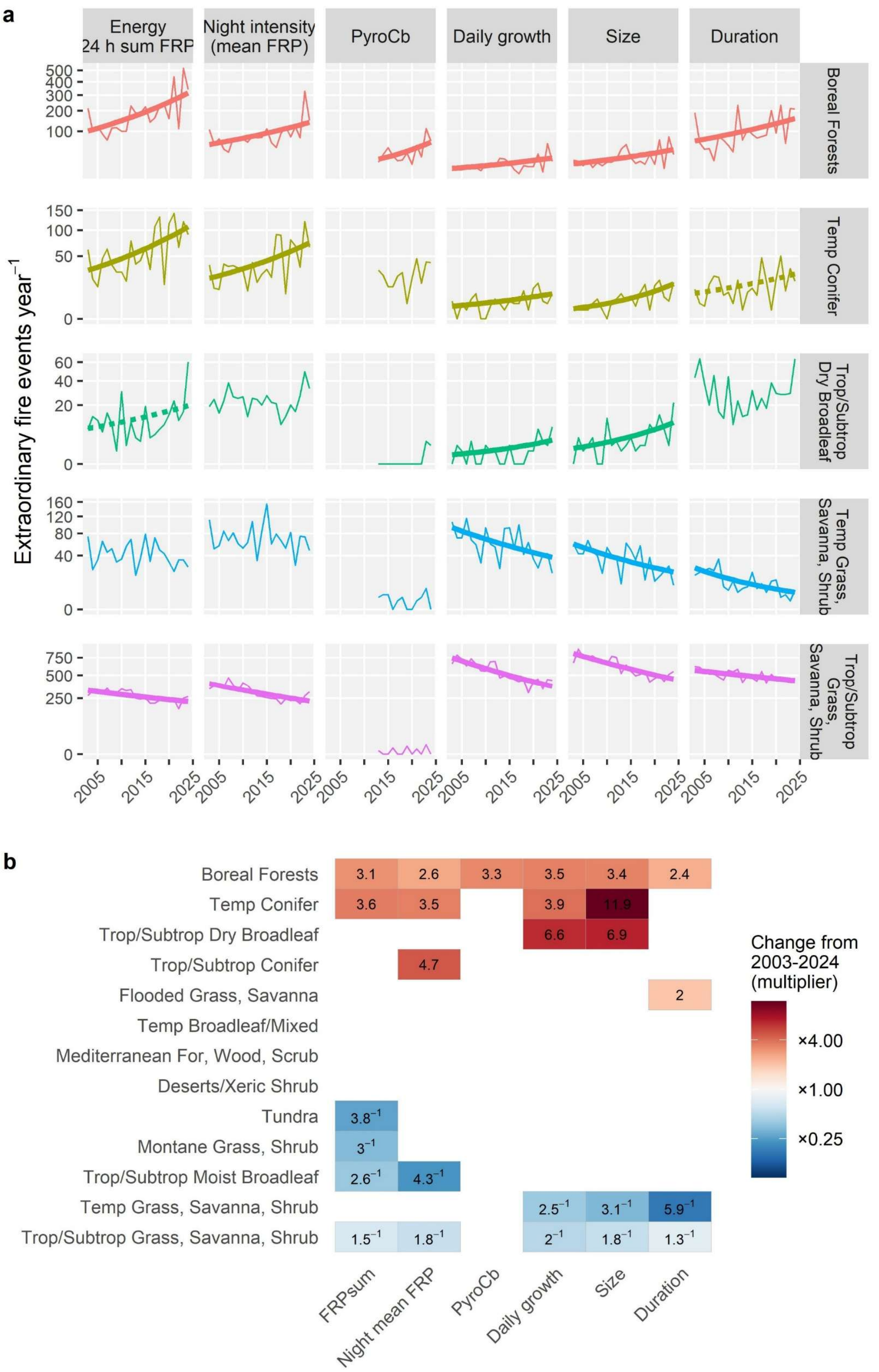


Figure 4. Temporal trends in extraordinary fire events. *Extraordinary events follow the description in Figure 2 and Supplementary Text 1.* ***(a)*** *Thin lines show the annual count of extraordinary events. Thick solid lines ($p < 0.05$) and thick dashed lines ($0.05 < p < 0.08$) show statistically significant and marginally significant trends of a generalised linear model (count ~ year; negative binomial distribution). Only the biomes with most change are shown here but see Supplementary Figure S1 for trends in all biomes. Y-axis is square-root-transformed.* ***(b)*** *Synthesis of statistically significant ($p < 0.05$) trends among biomes. Values are multipliers denoting the difference in the GLM fit from (a) for 2024 compared to 2003.*

Trends in socioeconomically extraordinary fires

Fires that are extraordinary by virtue of their socioeconomic effects have increased substantially in the last decade. For example, systematic data on economic losses show that extreme economic loss events have increased by 4.4-fold from 1980-2023[58]. So too have major fatality events (≥ 10 fatalities), which have tripled over the same period[58]. Several very significant fatality events have occurred in the last three years, with fires in Lahaina and Valparaiso both causing more than 100 direct fatalities[7,17]. Despite an increase in events leading to more than 10 fatalities[58], extremely large fatality events from earlier centuries, such as Peshtigo (USA, 1871) and Kursha-2 (Russia, 1936) that each killed >1,000 people, suggest modern advances in preparedness and suppression have helped to reduce the magnitude of modern extreme fatality events.

Only one global study has defined trends in exposure to extreme smoke concentrations[98]. Using the 95th percentile of population-weighted exposure to wildfire $PM_{2.5}$, they found that exposure to extreme days grew from an average of 16 in 1990–1999, to 45.8 in 2000–2009, and 66.1 between 2010–2018[98]. Similarly, identifying extraordinary population smoke impacts by applying the 99.9th percentile (~50 $\mu g\ m^{-3}$) to a global dataset of wildfire $PM_{2.5}$ concentration (2003-2024)[81] indicates a ~47% increase for the decade 2014-2024 compared with 2003-2013 (Figure S3).

4. Drivers of globally extraordinary wildfires

Below we briefly consider a range of societal and biophysical factors that influence the occurrence of extraordinary fires, highlighting broad mechanisms—climate change, land stewardship, fuel dynamics, human exposure, and ignitions—that collectively help explain the recent surge in some extraordinary events.

4.1 Climate drivers

Climate and weather play overarching roles in extraordinary wildfires, though their influence differs among ecosystems depending on the key limitations on fire. Fire in fuel-rich biomes is usually constrained by the requirement of dry fuel and conducive weather, whereas more arid systems are primarily limited by productivity and fuel[99]. In broad support of this pattern, extraordinary fire events (from Fig 2) were tightly associated with periods of extreme drought and fire weather in cool, moist or fuel-rich biomes, such as temperate forests, boreal forests, and tundra (Fig 5). In contrast, extraordinary fires in grasslands and desert biomes were either weakly connected or unconnected to anomalous drought (Fig 5a) and less strongly associated with anomalous fire weather (Fig 5b). Instead, extraordinary arid-zone fires – such as the very large and fast-growing fires in arid central Australia in 2023[100] – typically occur after wet, productive years that generate plentiful fuels.

Climate change is intensifying the climate conditions linked with extraordinary fires at multiple timescales. This ranges from chronic warming and drying trends[101] to rapid flash droughts[102] and compound weather extremes such as the coincidence of strong winds, low humidity, and dry fuels[103,104]. Critically important is the air's drying capacity[105], with climate change exacerbating both mean[106] and extreme[107] vapor pressure deficit (VPD). Increasing VPD leads to drier dead fuels[108], as well as causing plant death, which converts live fuels to dead fuels. Relatedly, days with extreme Fire Weather Index emerged beyond historic variability over ~20% of the world by 2019, with 3 °C warming predicted to drive twice the emergence as 2 °C[104]. Increasing swings between wet periods that promote fuel growth and dry periods that elevate flammability – termed hydroclimatic whiplash[109] – further promote extraordinary fire in some biomes[110]. Complicating these effects is the effect of CO_2 fertilization, which in some systems could plausibly increase vegetation growth and fuel loads[111]. Collectively, these climatic changes generally increase landscape receptivity to ignitions and drive more aggressive fire behaviour.

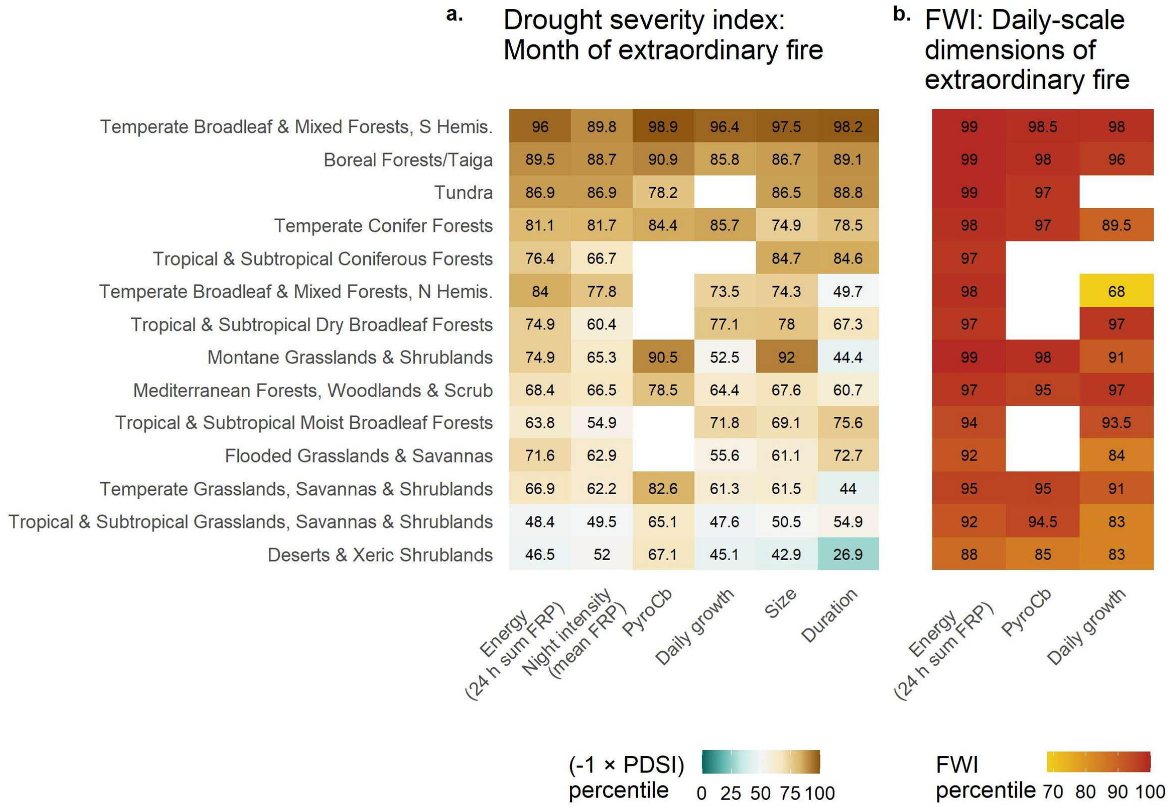


Figure 5. Drought and fire weather coinciding with extraordinary fire events. *Extraordinary fire events are those from Fig 2.* ***(a)*** *Monthly Palmer Drought Severity Index (PDSI) for the month of fire onset was derived from ERA5 precipitation [112] and Penman–Monteith[113] evapotranspiration using a standard water-balance formulation[114], then inverted (× −1) to represent increasing drought stress.* ***(b)*** *Canadian Fire Weather Index[115] (FWI) for the subset of dimensions of extraordinary fire events measured at a daily time scale. Percentiles were calculated for the period 2002-2023. Numbers indicate median values, with categories with fewer than five events omitted. Biomes are ordered from strongest to weakest overall association with PDSI.*

Recent fire seasons illustrate these dynamics. In southeastern Australia, the record-breaking 2019/20 Black Summer coincided with exceptionally rare weather[116] in the nation's hottest and driest year on record[4], resulting in landscape-scale dry forest fuel devoid of the moist topographic barriers that typically constrain fire spread. Similarly, Canada's unprecedented 2023 fire season occurred in a year 2.2 °C warmer than the 1991–2020 average, producing the most extreme fire weather since the beginning of the time series in 1940[2]. Formal attribution studies show that anthropogenic climate change has markedly increased the likelihood of such events worldwide[32] and regionally[17,117,118]. For example, extreme fire weather in western Amazonia in October 2023 was made 20–28 times more likely by human-driven warming[17]. Together, these cases demonstrate that climate change is amplifying the conditions that underpin extraordinary fire events.

4.2 Fuel dynamics and land use

Fuel and land-use practices shape the likelihood and behaviour of extraordinary fires. While fire suppression has clearly prevented losses, saved lives, and averted instances that may have otherwise become extraordinary fires, the legacy of sustained over-suppression – the "fire suppression paradox" – has led to fuel accumulation in vegetation historically shaped by fire but now sheltered from it[119,120]. This process predisposes fires to burn more intensely when they inevitably occur. Tightly related is the disruption of Indigenous fire stewardship, which in regions including Australia and North America has led to a reduction in fine-scale anthropogenic fire, leading to woody thickening and more uncontrolled fire[121-124]. In other regions including southern Europe, Chile, and western Amazonia, rural depopulation and abandonment of pastoral practices have led to an increase in unmanaged vegetation and fuel accumulation[62,125-127].

In addition to a lack of fire and woody thickening, exotic species have altered fuels in ways that further exacerbate fire activity. In some regions, invasive grasses and shrubs have replaced native species; for example, in Australia, invasion of gamba grass (*Andropogon gayanus*)[128] and buffel grass (*Cenchrus ciliaris*)[129] have led to intensified fires, while across the USA at least 8 species of invasive grasses have been linked to exacerbated fire regimes[130]. Commercial plantation of exotic (and native) species, such as *Eucalyptus* and *Pinus radiata* in Chile[62] has led to dense, even-age stands that are highly flammable.

4.3 Human expansion, exposure, and ignitions

Expanding human populations are likely contributing to the rising occurrence of fires with high socioeconomic consequences. Globally, the wildland-urban interface expanded by an estimated 36% (2000-2020)[131], and the number of people exposed to wildfire rose by ~40% (2002–2021) despite declining area burned[132]. Notably, the highest exposure occurs in Africa[132], where fires are most frequent but where fire disasters remain relatively rare, highlighting that disaster risk depends not only on exposure, but also on fire behaviour and the nature of human–fire interactions[58]. Broadly, rising human populations and expanding built environments in fire-prone locations are collectively raising the socioeconomic stakes of extraordinary wildfire.

Geographic patterns of settlement and land use also shape the ignition landscape. Many of the most destructive fire disasters were ignited directly or indirectly by human activity – whether through negligence, accidents, or deliberate actions. This contrasts with the lightning-driven ignition patterns of many large, environmentally impactful fire seasons[133] (for example, Canada 2023[2]). Powerline failures are a particularly important source of ignitions, linked to numerous disastrous fires (for example, Paradise, California[134]), alongside other forms of human negligence such escaped waste burn-offs (for example, Attica, Greece, 2018[135]). These human ignition sources – increasingly coinciding with landscapes primed by fuel loads and climate extremes – are expanding the spatial and temporal niche of fire[133,136], and by implication, expanding the scope for extraordinary fires.

5. Impacts of extraordinary wildfires

Extraordinary fire has immediate to lagged cascading socio-ecological effects at local, regional and international scales. These include disrupting ecosystems services, adversely affecting biodiversity, causing substantial economic costs and psychosocial harms. Given this complexity, we provide a sketch as to how these events can destabilise ecosystems and communities.

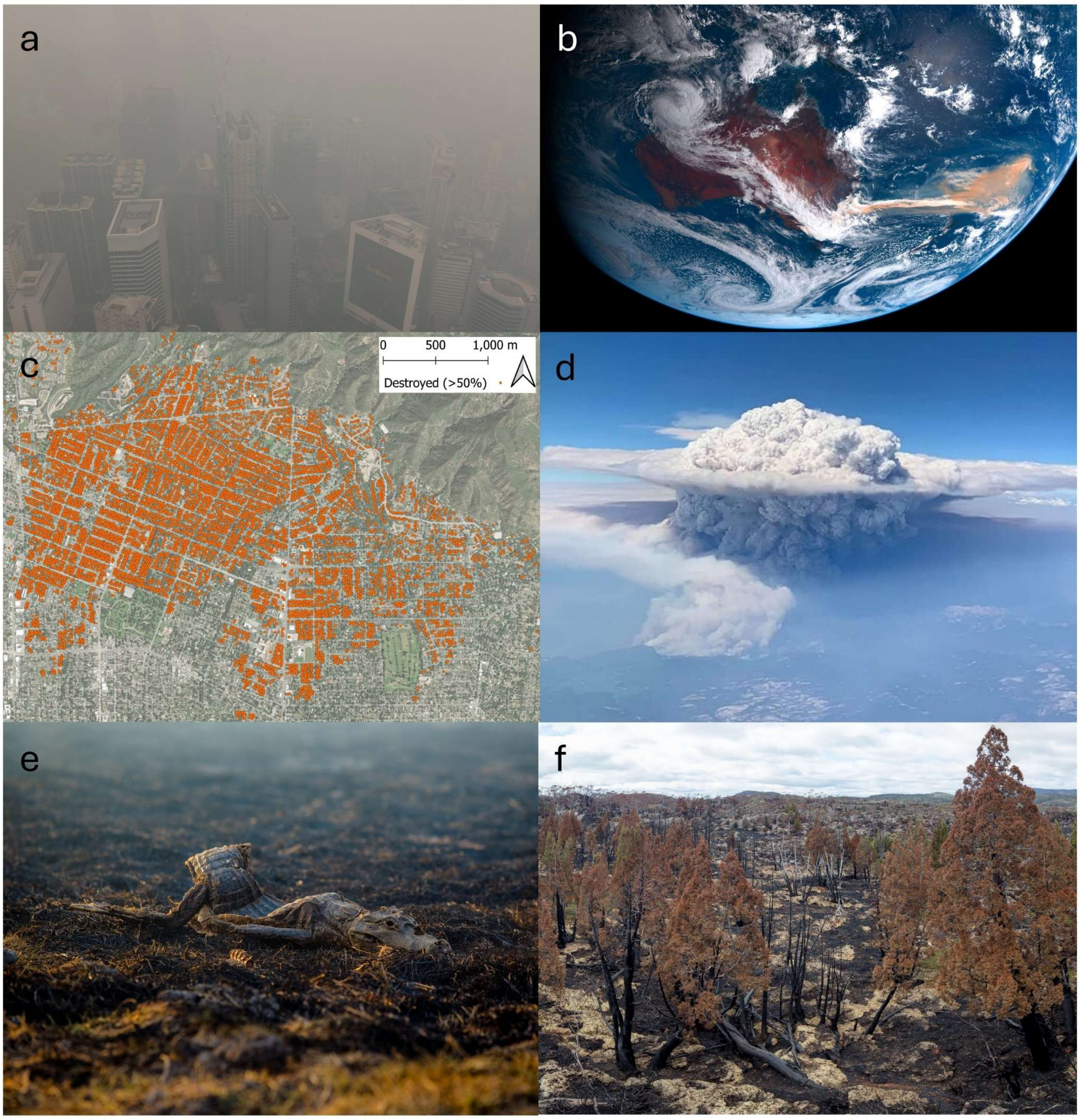


Fig 6. Diverse impacts of extraordinary fires. ***(a)*** *Smoke from the 2015 Indonesian fires led to extreme air pollution in Kuala Lumpur, Malaysia, where schools remained closed for days. Photo: stuartgr/depositphotos.* ***(b)*** *Long-distance transport of iron-iron rich aerosols from the 2019/20 Australian bushfires led to a large phytoplankton bloom in the Pacific Southern*

Ocean[137]. Photo: Himawari-8 satellite image, Japan Meteorological Agency. ***(c)*** *The Eaton Fire, Los Angeles, spread extraordinarily far into the city, destroying buildings more than 3 km and 21 blocks from the wildland-urban interface where many residents would have assumed themselves to be safe. Data: California Damage Inspections Data[138].* ***(d)*** *The 2020 Creek Fire in California generated explosive pyroCb activity, including producing extensive lightning and downdrafts that exacerbate fire spread[139]. One of the largest fires in California history, it was estimated to cost around $500 million in damages and firefighting costs. Photo: Thalia Dockery.* ***(e)*** *A dead caiman in an area burned by the 2020 Pantanal fires that devastated the world's largest tropical wetland, killing an estimated 17 million vertebrates in Brazil[35]. Photo: Luzo Reis/iStock.* ***(f)*** *A grove of ancient pencil pine (Athrotaxis cupressoides) killed by fire in 2016 at Lake Mackenzie, Tasmania, Australia. Pencil pines are a relictual Gondwanan conifer species that exist only in fire refugia and are threatened by paleocologically anomalous fire[53-55]. Photo: copyright Rob Blakers.*

5.1 Environmental effects

Extraordinary fires can fundamentally reshape ecosystems by pushing plant communities beyond their capacity for recovery. Forests burned by large-scale, severe fires have increasingly exhibited "recovery stagnation" in the last decade, especially in boreal forests and western North American conifer forests[140]. In other regions, anomalously short fire intervals can impose "interval squeeze," preventing trees from reaching reproductive maturity and potentially driving transformational shifts from forest to shrubland or grassland[141-143]. Such conversions reinforce flammability feedbacks by replacing relatively fire-resistant vegetation communities with more combustible assemblages. Fires in novel locations and at novel intervals can jeopardise species poorly adapted to fire beyond the bounds of historical fire regimes[55].

In contrast to plants, many animals, though not all, possess morphological, behavioural, and physiological traits that help them to evade fire[144]. Yet the same strategies that proved adaptive under historical fire regimes may be insufficient – or even maladaptive – in the face of extraordinary fires[145]. For example, all 17 radio-tracked frill-neck lizards (*Chlamydosaurus kingii*) safely evaded a low-intensity fire by climbing trees, but a quarter of 24 individuals died using the same strategy during a more intense fire[146,147]. Several authors have proposed that such events may exert strong selective pressure, favouring the evolution of more "fire-savvy" behavioural phenotypes[145,146,148-150], such as frill-neck lizards instead climbing non-flammable termite mounds[147], but these options are obviously limited in many landscapes with very severe fire. For example, slow-moving, arboreal koalas (*Phascolarctos cinereus*) have few escape options, and were extirpated in areas burned at high severity by the 2019/20 Australian fires, but unaffected in areas burned at low severity[151].

Extraordinary fires kill vast numbers of animals. The 2020 Pantanal fires were estimated to have killed 17 million vertebrates in Brazil[35] (Fig 6e), while the 2019–20 Australian bushfires affected roughly three billion animals, though not all lethally[152]. Despite such staggering figures, a global review of 31 studies found that most fires cause low direct animal mortality rates (~3%), with higher mortality under severe fire[146,153]. However, only one of those studies examined a fire exceeding 10,000 ha, underscoring just how little is known about animal mortality[153] as well as smoke impacts[154] during extreme fires. Impacts will clearly differ among taxonomic groups, but for many species, the flames themselves are less consequential than the post-fire "gauntlet"[146] – a period marked in some systems by increased activity of invasive predators[155,156], increased hunting success[157,158], acute resource scarcity, and a loss of refugia at various spatiotemporal scales[159,160]. In addition to constraining post-fire survival, the increasing loss of fire refugia, driven in part by extreme fires breaching typical landscape barriers, raises concerns for seeding the recolonisation process for both animals and plants.

Wildfires drive large exchanges of CO_2 between the terrestrial biosphere and the atmosphere. Under a stable fire regime, fire emissions initially deliver CO_2 to the atmosphere but are later compensated by the post-fire recovery of vegetation biomass to pre-fire levels[161,162]. Shifts in fire regime have potential to unsettle the balance between fire emissions and post-fire recovery fluxes[83,161,163]. Increased fire extent in carbon-rich environments, like forests and peatlands, and increased emissions per unit area burned, drive net losses of carbon to the atmosphere from some terrestrial ecosystems. For example, forest fire emissions have increased globally by 60% from 2001-2023[164], building on reports of enormous emissions from extreme forest[2,24,25,88,165] and peat[166-168] fire episodes spanning boreal, temperate and tropical regions. Critically, the loss of stored carbon from forests and peatlands contributes to accelerating climate-carbon cycle feedbacks[169], though interactions between surface reflectance and evapotranspiration may partially offset the accelerating climate feedback from net carbon loss[170].

Beyond these domains, extraordinary fires can trigger a vast suite of additional environmental effects. Severe fires can destabilise soils, induce hydrophobicity, and drive post-fire erosion and debris flows[171]; degrade water quality through influx of sediments, ash, and organic matter that leads to hypoxia[172]; and disrupt microbial and nutrient-cycling processes[173]. Distant transport of smoke has led to stratospheric ozone depletion[174], distant oceanic phytoplankton blooms[137] (Fig 6b), and black carbon deposition on the Greenland ice sheet, reducing albedo and potentially exacerbating melt rates[175]. The non-exhaustive collection of impacts in this section underscores that the environmental imprint of extraordinary fires extends across soils, waters, biota, oceans, and the climate.

5.2 Human impacts

Extraordinary fires pose immediate threats to human life, property, and livelihoods. Direct fatalities primarily occur when fast-moving fires overwhelm evacuation or suppression capacity, often in the WUI where exposure is greatest. The widespread introduction of modern suppression and evacuation systems has substantially reduced the occurrence of extreme fatality events, such as individual fires that claimed more than a thousand lives in the 18th and 19th centuries[176]. Nevertheless, direct mortality and structure loss have risen over recent decades, particularly in the extratropics[21]. Mass evacuations displacing tens of thousands of residents have become increasingly common, though only Canada systematically tracks them[177]. In addition to structure loss, increasing immediate economic losses from extraordinary fires stem from destroyed municipal infrastructure, disrupted commerce along closed transportation corridors, destroyed livestock, crops burned or tainted by smoke, and lost revenue from disrupted industries[178-182].

While direct fatalities and destruction occur within firegrounds, the greatest health burden arises from smoke, whose effects extend across broader regions (Fig 1a-b). As discussed earlier (Box 1), extreme smoke impacts often stem from extraordinary fire seasons rather than single extreme events (e.g., Indonesia 2015, Australia 2019–20, Canada 2023). Nevertheless, the toll of smoke far exceeds that of the flames themselves: the 2025 Los Angeles fire disaster, for example, caused 31 direct deaths but an estimated 440 excess fatalities linked to smoke exposure[183]. Additionally, such episodic smoke events are linked with population-wide increases in respiratory, cardiovascular and neurological diseases, and adverse birth outcomes[184].

Even once the flames are extinguished, cascading consequences can persist for years to decades. Municipal drinking-water supplies may be immediately compromised through damage to treatment and delivery infrastructure[185], and subsequently by contamination from burned catchments experiencing erosion and sedimentation[186,187]. The loss of this critical ecosystem service contributes to delayed or absent rebuilding and, in some cases, long-term community decline or permanent depopulation[188]. Displaced residents – particularly those lacking insurance[189] – face compounding challenges in accessing rebuilding resources[190], amid economic collapse and job loss[188,191] and the loss of essential services[192-194]. Housing markets can become destabilised: in high-demand areas, reduced supply drives up prices and eliminates affordable housing that once supported vulnerable residents[188,195,196], while in other regions, declining demand and persistent risk perceptions depress property values[197]. Mounting losses have also pushed insurance markets to the brink of collapse, with rising premiums and policy non-renewals undermining community stability[193,198-200].

Over longer timescales, extraordinary fires can permanently alter the demographic and cultural character of communities. Ownership patterns often shift as reconstruction favours wealthier or absentee owners[193], while historically significant communities risk being displaced by the high costs of rebuilding. Indigenous peoples face particularly severe social costs when fires damage tight-knit social networks, traditional homelands, and culturally significant places[201]. Survivors frequently grapple with psychological trauma, including post-traumatic stress disorder, grief, and diminished quality of life[202-205]. These mental health challenges are exacerbated in some regions, such as California, when preventative power shutoffs, coupled with lingering trauma from prior fire exposure, can retraumatise survivors[206]. Burdens extend to those on the front lines: wildland firefighters exhibit rising rates of mental-health episodes and suicide, aggravated by extreme working conditions, temporary employment, and insufficient institutional support[207,208].

6. Summary and future directions

Extraordinary wildfires are multidimensional phenomena, defined by their attributes, behaviour or impacts. This Review highlights that different approaches for characterising extraordinary fires are complementary but incommensurate. We offer an operating definition of extraordinary fires and apply it to some dimensions monitored by remote sensing this century, revealing the distinct geographic patterns of different typologies of extraordinary fires (Fig 2). The most pronounced increases in extraordinary fires this century have occurred in boreal and temperate conifer forests, whereas their frequency in tropical savannas is declining (Fig 3). Drivers are complex: extraordinary fires in forest biomes are tightly linked to drought and extreme fire weather, whereas these relationships are weak or absent in tropical savannas and deserts (Fig 5). In regions where weather and drought exert an outsized influence on extraordinary fires, we can therefore have the highest confidence that intensifying fire weather[209] will amplify the chance of extraordinary fire events.

Perhaps the biggest challenge in tracking extraordinary fires globally stems from data constraints. Short-term global datasets pose challenges for establishing natural baselines. Paleo records, on the other hand, extend data centuries to millennia but are not available globally, suggesting efforts to integrate these different data types[210] hold promise for identifying extraordinary fires across temporal scales and shifting baselines[211]. Data are even more fragmented for socioeconomic dimensions of fire[212,213]. Because economic data are often kept private by governments or insurers, there is a clear need for standardisation of global datasets involving economic and health impacts, fire suppression efforts, and individual building destruction[212,213], especially given these organisations stand to benefit from mitigation improvements.

Case studies provide key mechanistic knowledge, such as fine-scale understanding of fuel, that cannot be gleaned from remote sensing alone. Although new initiatives endeavour to evaluate extreme fires annually[17,214], the broader literature remains biased towards wealthier countries, such as the United States, Canada, and Australia, which may in turn bias our perceptions of the geography of extraordinary fires. While major advances have been made in probabilistic attribution to anthropogenic climate change[32,104,116-118,215], it remains more challenging to quantify the influence of other processes, such as fuel mitigation and suppression responses. Greater investment in detailed case studies, especially from underrepresented regions, is required for comprehensive understanding of the mechanisms that produce extraordinary fires and their impacts.

Technological innovation will be central to advancing our understanding and management of extraordinary fires. LiDAR is improving measurements of pre-fire fuels[216] and post-fire severity[217]. Emerging tools such as uncrewed aerial systems[218], constellations of low-Earth-orbit satellites[219], and geostationary satellites[220] are transforming our capacity to monitor fire behaviour and impacts in real time. There is considerable scope for developing sensors capable of mapping fire fronts and intensities at fine spatiotemporal resolutions, but for maximal utility, this must contend with inherent trade-offs between temporal and spatial resolution (i.e., frequent observations occur at coarse spatial resolution[220], and vice versa). Critically, many processes and feedback mechanisms linked to extreme fires remain poorly understood, and consequently, computational models poorly capture the fire-atmosphere interactions that drive rapid escalation[221]. Addressing this gap requires comprehensive field measurements from within and above active fire zones to constrain the drivers of extraordinary fire behaviour (for example, the INjected Smoke and PYRocumulonimbus Experiment, 2026-2027[222]).

As climate change reshapes temperature, moisture, and vegetation regimes, it is generating novel climates[29,223] and ecosystems[224]. By extension, novel climates may generate fire events with no historical analogue[29], characterised by climate–fuel–fire interactions not yet seen[225]. Thus, under continued warming, entirely new forms of extraordinary fire may emerge. Relying on historical experience alone will become increasingly insufficient, heightening the need for predictive modelling frameworks – a central challenge for future wildfire science.

This Review provides a foundation for tracking and understanding extraordinary wildfire events globally, linking their defining characteristics, drivers, and consequences. Extraordinary fires have distinct pyrogeographic fingerprints, and some biomes have experienced substantial increases this century. Adapting to a world increasingly faced with extraordinary fire will require urgent coordinated efforts across science, policy, and practice.

References

1 Bowman, D. M. J. S. *et al.* Vegetation fires in the Anthropocene. *Nature Reviews Earth & Environment* **1**, 500-515 (2020). https://doi.org:10.1038/s43017-020-0085-3

2 Jain, P. *et al.* Drivers and Impacts of the Record-Breaking 2023 Wildfire Season in Canada. *Nature Communications* **15**, 6764 (2024). https://doi.org:10.1038/s41467-024-51154-7

3 Libonati, R. *et al.* Assessing the role of compound drought and heatwave events on unprecedented 2020 wildfires in the Pantanal. *Environmental Research Letters* **17**, 015005 (2022). https://doi.org:10.1088/1748-9326/ac462e

4 Abram, N. J. *et al.* Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Communications Earth & Environment* **2**, 8 (2021). https://doi.org:10.1038/s43247-020-00065-8

5 Troy, A. *et al.* An analysis of factors influencing structure loss resulting from the 2018 Camp Fire. *International Journal of Wildland Fire* **31**, 586-598 (2022). https://doi.org:https://doi.org/10.1071/WF21176

6 Mamuji, A. A. & Rozdilsky, J. L. Wildfire as an increasingly common natural disaster facing Canada: understanding the 2016 Fort McMurray wildfire. *Natural Hazards* **98**, 163-180 (2019). https://doi.org:10.1007/s11069-018-3488-4

7 González, M. E., Syphard, A. D., Fischer, A. P., Muñoz, A. A. & Miranda, A. Chile's Valparaíso hills on fire. *Science* **383**, 1424-1424 (2024). https://doi.org:10.1126/science.ado5411

8 Filkov, A. I., Ngo, T., Matthews, S., Telfer, S. & Penman, T. D. Impact of Australia's catastrophic 2019/20 bushfire season on communities and environment. Retrospective analysis and current trends. *Journal of Safety Science and Resilience* **1**, 44-56 (2020). https://doi.org:https://doi.org/10.1016/j.jnlssr.2020.06.009

9 Brown, T. & Shelton, J. Confluence of fire and people. *Nature Sustainability* **8**, 329-330 (2025). https://doi.org:10.1038/s41893-025-01541-9

10 Sharples, J. J. *et al.* Natural hazards in Australia: extreme bushfire. *Climatic Change* **139**, 85-99 (2016). https://doi.org:10.1007/s10584-016-1811-1

11 Tedim, F. *et al.* Defining extreme wildfire events: Difficulties, challenges, and impacts. *Fire* **1**, 9 (2018).

12 Balch, J. K. *et al.* Social-Environmental Extremes: Rethinking Extraordinary Events as Outcomes of Interacting Biophysical and Social Systems. *Earth's Future* **8**, e2019EF001319 (2020). https://doi.org:https://doi.org/10.1029/2019EF001319

13 Johnston, F. H. *et al.* Unprecedented health costs of smoke-related PM2.5 from the 2019–20 Australian megafires. *Nature Sustainability* **4**, 42-47 (2021). https://doi.org:10.1038/s41893-020-00610-5

14 Collins, L. *et al.* The 2019/2020 mega-fires exposed Australian ecosystems to an unprecedented extent of high-severity fire. *Environmental Research Letters* **16**, 044029 (2021). https://doi.org:10.1088/1748-9326/abeb9e

15 Boer, M. M., Resco de Dios, V. & Bradstock, R. A. Unprecedented burn area of Australian mega forest fires. *Nature Climate Change* **10**, 171-172 (2020). https://doi.org:10.1038/s41558-020-0716-1

16 Sullivan, A. *et al.* Spreading like wildfire: The rising threat of extraordinary landscape fires. (2022).

17 Jones, M. W. *et al.* State of Wildfires 2023–2024. *Earth Syst. Sci. Data* **16**, 3601-3685 (2024). https://doi.org:10.5194/essd-16-3601-2024

18 Linley, G. D. *et al.* What do you mean, 'megafire'? *Global Ecology and Biogeography* **31**, 1906-1922 (2022). https://doi.org:https://doi.org/10.1111/geb.13499
19 Cunningham, C. X., Williamson, G. J. & Bowman, D. M. J. S. Increasing frequency and intensity of the most extreme wildfires on Earth. *Nature Ecology & Evolution* (2024). https://doi.org:https://doi.org/10.1038/s41559-024-02452-2
20 Balch, J. K. *et al.* The fastest-growing and most destructive fires in the US (2001 to 2020). *Science* **386**, 425-431 (2024). https://doi.org:doi:10.1126/science.adk5737
21 Cunningham, C. X. *et al.* Climate-linked escalation of societally disastrous wildfires. *EcoEvoRxiv [PREPRINT]** (2024).
22 Fromm, M., Servranckx, R., Stocks, B. J. & Peterson, D. A. Understanding the critical elements of the pyrocumulonimbus storm sparked by high-intensity wildland fire. *Communications Earth & Environment* **3**, 243 (2022). https://doi.org:10.1038/s43247-022-00566-8
23 Luo, K., Wang, X., de Jong, M. & Flannigan, M. Drought triggers and sustains overnight fires in North America. *Nature* **627**, 321-327 (2024). https://doi.org:10.1038/s41586-024-07028-5
24 Byrne, B. *et al.* Carbon emissions from the 2023 Canadian wildfires. *Nature* (2024). https://doi.org:10.1038/s41586-024-07878-z
25 van der Velde, I. R. *et al.* Vast CO2 release from Australian fires in 2019–2020 constrained by satellite. *Nature* **597**, 366-369 (2021). https://doi.org:10.1038/s41586-021-03712-y
26 Bowman, D. M. J. S. Conflagrations and the Wisdom of Aboriginal Sacred Knowledge. *Fire* **4**, 88 (2021).
27 Doerr, S. H. & Santín, C. Global trends in wildfire and its impacts: perceptions versus realities in a changing world. *Philosophical Transactions of the Royal Society B: Biological Sciences* **371**, 20150345 (2016). https://doi.org:doi:10.1098/rstb.2015.0345
28 Iglesias, V. *et al.* Fires that matter: reconceptualizing fire risk to include interactions between humans and the natural environment. *Environmental Research Letters* **17**, 045014 (2022). https://doi.org:10.1088/1748-9326/ac5c0c
29 Duane, A., Castellnou, M. & Brotons, L. Towards a comprehensive look at global drivers of novel extreme wildfire events. *Climatic Change* **165**, 43 (2021). https://doi.org:10.1007/s10584-021-03066-4
30 Linley, G. D. *et al.* 'Megafire'—You May Not Like It, But You Cannot Avoid It. *Global Ecology and Biogeography* **34**, e70032 (2025). https://doi.org:https://doi.org/10.1111/geb.70032
31 Bowman, D. M. J. S. *et al.* Human exposure and sensitivity to globally extreme wildfire events. *Nature Ecology & Evolution* **1**, 0058 (2017). https://doi.org:10.1038/s41559-016-0058
32 Abatzoglou, J. T. *et al.* Climate change has increased the odds of extreme regional forest fire years globally. *Nature Communications* **16**, 6390 (2025). https://doi.org:10.1038/s41467-025-61608-1
33 Fire Safety Research Institute, K., S., and Alkonis, D. Lahaina Fire Comprehensive Timeline Report. DOI: https://doi.org/10.54206/102376/VQKQ5427. (2024).
34 Fortin, J., & Hassan, A. . Death Toll of Maui Wildfire Now at 102. New York Times. Retrieved August 10, 2025 from https://www.nytimes.com/article/maui-wildfire-victims.html#:~:text=A%20large%20number%20of%20victims,died%20along%20a%20single%20street. (2024).
35 Tomas, W. M. *et al.* Distance sampling surveys reveal 17 million vertebrates directly killed by the 2020's wildfires in the Pantanal, Brazil. *Scientific Reports* **11**, 23547 (2021). https://doi.org:10.1038/s41598-021-02844-5

36 Mataveli, G. A. V. *et al.* 2020 Pantanal's widespread fire: short- and long-term implications for biodiversity and conservation. *Biodiversity and Conservation* **30**, 3299-3303 (2021). https://doi.org:10.1007/s10531-021-02243-2

37 Libonati, R., DaCamara, C. C., Peres, L. F., Sander de Carvalho, L. A. & Garcia, L. C. Rescue Brazil's burning Pantanal wetlands. *Nature* **588**, 217-219 (2020).

38 Nolan, R. H. *et al.* What Do the Australian Black Summer Fires Signify for the Global Fire Crisis? *Fire* **4** (2021). <https://mdpi-res.com/d_attachment/fire/fire-04-00097/article_deploy/fire-04-00097.pdf?version=1639752484>.

39 Peterson, D. A. *et al.* Worldwide inventory reveals the frequency and variability of pyrocumulonimbus and stratospheric smoke plumes during 2013-2023. *npj Climate and Atmospheric Science* **8** (2025). https://doi.org:https://doi.org/10.1038/s41612-025-01188-5

40 Elignon, J. Wildfire Rips Through One of Africa's Largest National Parks. *New York Times* (2025).

41 Johnston, F. H. *et al.* Estimated Global Mortality Attributable to Smoke from Landscape Fires. *Environmental Health Perspectives* **120**, 695-701 (2012). https://doi.org:doi:10.1289/ehp.1104422

42 Koplitz, S. N. *et al.* Public health impacts of the severe haze in Equatorial Asia in September–October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure. *Environmental Research Letters* **11**, 094023 (2016). https://doi.org:10.1088/1748-9326/11/9/094023

43 Keeley, J. E. Fire intensity, fire severity and burn severity: a brief review and suggested usage. *International Journal of Wildland Fire* **18**, 116-126 (2009). https://doi.org:https://doi.org/10.1071/WF07049

44 Plucinski, M. P. Fighting Flames and Forging Firelines: Wildfire Suppression Effectiveness at the Fire Edge. *Current Forestry Reports* **5**, 1-19 (2019). https://doi.org:10.1007/s40725-019-00084-5

45 Kaiser, J. W. *et al.* Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power. *Biogeosciences* **9**, 527-554 (2012). https://doi.org:10.5194/bg-9-527-2012

46 Wooster, M. J., Roberts, G., Perry, G. L. W. & Kaufman, Y. J. Retrieval of biomass combustion rates and totals from fire radiative power observations: FRP derivation and calibration relationships between biomass consumption and fire radiative energy release. *Journal of Geophysical Research: Atmospheres* **110** (2005). https://doi.org:https://doi.org/10.1029/2005JD006318

47 Peterson, D. A. *et al.* Australia's Black Summer pyrocumulonimbus super outbreak reveals potential for increasingly extreme stratospheric smoke events. *npj Climate and Atmospheric Science* **4**, 38 (2021). https://doi.org:10.1038/s41612-021-00192-9

48 Greenwood, L. *et al.* Indigenous pyrodiversity promotes plant diversity. *Biological Conservation* **291**, 110479 (2024). https://doi.org:https://doi.org/10.1016/j.biocon.2024.110479

49 Bowman, D. M. J. S. *et al.* Pyrodiversity is the coupling of biodiversity and fire regimes in food webs. *Philosophical Transactions of the Royal Society B: Biological Sciences* **371**, 20150169 (2016). https://doi.org:doi:10.1098/rstb.2015.0169

50 Lareau, N. P. Plume Dynamics Drive Extreme Long-Range Spotting During California's Dixie Fire. *Journal of Geophysical Research: Atmospheres* **130**, e2024JD043167 (2025). https://doi.org:https://doi.org/10.1029/2024JD043167

51 Cruz, M. G. *et al.* Anatomy of a catastrophic wildfire: The Black Saturday Kilmore East fire in Victoria, Australia. *Forest Ecology and Management* **284**, 269-285 (2012). https://doi.org:https://doi.org/10.1016/j.foreco.2012.02.035

52 Balch, J. K. *et al.* Warming weakens the night-time barrier to global fire. *Nature* **602**, 442-448 (2022). https://doi.org:10.1038/s41586-021-04325-1

53 Bowman, D. M., Rodriguez-Cubillo, D. & Prior, L. D. in *Ecosystem collapse and climate change* 133-153 (Springer, 2021).

54 Bergstrom, D. M. *et al.* Combating ecosystem collapse from the tropics to the Antarctic. *Global Change Biology* **27**, 1692-1703 (2021). https://doi.org:https://doi.org/10.1111/gcb.15539

55 Harris, R. M. B. *et al.* Biological responses to the press and pulse of climate trends and extreme events. *Nature Climate Change* **8**, 579-587 (2018). https://doi.org:10.1038/s41558-018-0187-9

56 Xu, R. *et al.* Global, regional, and national mortality burden attributable to air pollution from landscape fires: a health impact assessment study. *The Lancet* **404**, 2447-2459 (2024). https://doi.org:10.1016/S0140-6736(24)02251-7

57 Virkkala, A.-M. *et al.* Wildfires offset the increasing but spatially heterogeneous Arctic–boreal CO2 uptake. *Nature Climate Change* **15**, 188-195 (2025). https://doi.org:10.1038/s41558-024-02234-5

58 Cunningham, C. X. *et al.* Climate-linked escalation of societally disastrous wildfires. *Science* **390**, 53-58 (2025). https://doi.org:10.1126/science.adr5127

59 Flavelle, C., Cowan, J. & Penn, I. in *New York Times* (2023).

60 Newman Thacker, F. E. *et al.* In this current wildfire crisis, acknowledge widespread suffering. *Ambio* **54**, 759-773 (2025). https://doi.org:10.1007/s13280-024-02105-5

61 Evans, J. *et al.* Birth Outcomes, Health, and Health Care Needs of Childbearing Women following Wildfire Disasters: An Integrative, State-of-the-Science Review. *Environmental Health Perspectives* **130**, 086001 (2022). https://doi.org:doi:10.1289/EHP10544

62 Bowman, D. M. *et al.* Human–environmental drivers and impacts of the globally extreme 2017 Chilean fires. *Ambio* **48**, 350-362 (2019).

63 Gavin, D. G. *et al.* Forest fire and climate change in western North America: insights from sediment charcoal records. *Frontiers in Ecology and the Environment* **5**, 499-506 (2007). https://doi.org:https://doi.org/10.1890/060161

64 Fung, M. K., Schaller, M. F., Hoff, C. M., Katz, M. E. & Wright, J. D. Widespread and intense wildfires at the Paleocene-Eocene boundary. *Geochemical Perspectives Letters* **10**, 1-6 (2019). https://doi.org:https://doi.org/10.7185/geochemlet.1906

65 Roos, C. I. *et al.* Tree rings reveal persistent Western Apache (Ndee) fire stewardship and niche construction in the American Southwest. *Proceedings of the National Academy of Sciences* **122**, e2509169122 (2025). https://doi.org:doi:10.1073/pnas.2509169122

66 Holz, A., Haberle, S., Veblen, T. T., De Pol-Holz, R. & Southon, J. Fire history in western Patagonia from paired tree-ring fire-scar and charcoal records. *Clim. Past* **8**, 451-466 (2012). https://doi.org:10.5194/cp-8-451-2012

67 Roos, C. I. *et al.* Fire Suppression Impacts on Fuels and Fire Intensity in the Western U.S.: Insights from Archaeological Luminescence Dating in Northern New Mexico. *Fire* **3** (2020).

68 Schroeder, W., Csiszar, I. & Morisette, J. Quantifying the impact of cloud obscuration on remote sensing of active fires in the Brazilian Amazon. *Remote Sensing of Environment* **112**, 456-470 (2008).

69 Giglio, L., Schroeder, R. L., Hall, J. V. & Justice, C. MODIS Collection 6 and Collection 6.1 Active Fire Product User's Guide. NASA. (2021).

70 Giglio, L., Justice, C., Boschetti, L. & Roy, D. MODIS/Terra+Aqua Burned Area Monthly L3 Global 500m SIN Grid V061 [Data set]. NASA Land Processes Distributed Active Archive Center. https://doi.org/10.5067/MODIS/MCD64A1.061 Date Accessed: 2025-08-18. (2021).

71 Otón, G., Lizundia-Loiola, J., Pettinari, M. L. & Chuvieco, E. Development of a consistent global long-term burned area product (1982–2018) based on AVHRR-LTDR data. *International Journal of Applied Earth Observation and Geoinformation* **103**, 102473 (2021). https://doi.org:https://doi.org/10.1016/j.jag.2021.102473

72 Picotte, J. J. *et al.* Changes to the Monitoring Trends in Burn Severity program mapping production procedures and data products. *Fire Ecology* **16**, 16 (2020). https://doi.org:10.1186/s42408-020-00076-y

73 Hanes, C. *et al.* Fire regime changes in Canada: an update. *Canadian Journal of Forest Research* (2025). https://doi.org:10.1139/cjfr-2025-0209

74 Andela, N. *et al.* The Global Fire Atlas of individual fire size, duration, speed and direction. *Earth Syst. Sci. Data* **11**, 529-552 (2019). https://doi.org:10.5194/essd-11-529-2019

75 Dowdy, A. J., Fromm, M. D. & McCarthy, N. Pyrocumulonimbus lightning and fire ignition on Black Saturday in southeast Australia. *Journal of Geophysical Research: Atmospheres* **122**, 7342-7354 (2017). https://doi.org:https://doi.org/10.1002/2017JD026577

76 Wilson, C. S., Sharples, J. J. & Evans, J. P. Atmospheric profiles associated with pyrocumulonimbus in southeast Australia. *Scientific Reports* **15**, 38538 (2025). https://doi.org:10.1038/s41598-025-22530-0

77 Dinerstein, E. *et al.* An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm. *BioScience* **67**, 534-545 (2017). https://doi.org:10.1093/biosci/bix014

78 Heaney, A. *et al.* Impacts of Fine Particulate Matter From Wildfire Smoke on Respiratory and Cardiovascular Health in California. *Geohealth* **6**, e2021GH000578 (2022). https://doi.org:10.1029/2021gh000578

79 Hu, Y. *et al.* Global high-resolution fire-sourced PM2.5 concentrations for 2000–2023. *Earth Syst. Sci. Data* **17**, 3741-3756 (2025). https://doi.org:10.5194/essd-17-3741-2025

80 Xu, R. *et al.* Global population exposure to landscape fire air pollution from 2000 to 2019. *Nature* **621**, 521-529 (2023). https://doi.org:10.1038/s41586-023-06398-6

81 Hänninen, R., Sofiev, M., Uppstu, A. & Sofiev, M. *Daily surface concentration of fire related PM2.5 for 2003-2021, modelled by SILAM CTM when using the MODIS satellite data for the fire radiative power. Finish Meterological Institute. URL: https://fmi.b2share.csc.fi/records/1z7f5-rbe72*, 2023).

82 Abatzoglou, J. T., Williams, A. P., Boschetti, L., Zubkova, M. & Kolden, C. A. Global patterns of interannual climate–fire relationships. *Global Change Biology* **24**, 5164-5175 (2018). https://doi.org:https://doi.org/10.1111/gcb.14405

83 Jones, M. W. *et al.* Global and Regional Trends and Drivers of Fire Under Climate Change. *Reviews of Geophysics* **60**, e2020RG000726 (2022). https://doi.org:https://doi.org/10.1029/2020RG000726

84 Canadian Interagency Forest Fire Centre. *Wildfire Graphs. Accessed on Nov 5 2025. URL: https://ciffc.net/statistics*, 2025).

85 Scholten, R. C., Coumou, D., Luo, F. & Veraverbeke, S. Early snowmelt and polar jet dynamics co-influence recent extreme Siberian fire seasons. *Science* **378**, 1005-1009 (2022). https://doi.org:doi:10.1126/science.abn4419

86 Tomshin, O. & Solovyev, V. Features of the Extreme Fire Season of 2021 in Yakutia (Eastern Siberia) and Heavy Air Pollution Caused by Biomass Burning. *Remote Sensing* **14** (2022).

87 He, X., Sun, J., Yu, S. & Zhang, M. Regime shift in extreme wildfires within northern Eurasia and their impacts. *Environmental Research Letters* **20**, 114018 (2025). https://doi.org:10.1088/1748-9326/ae0b92

88 Zheng, B. *et al.* Record-high CO₂ emissions from boreal fires in 2021. *Science* **379**, 912-917 (2023). https://doi.org:doi:10.1126/science.ade0805

89 Iglesias, V., Balch, J. K. & Travis, W. R. U.S. fires became larger, more frequent, and more widespread in the 2000s. *Science Advances* **8**, eabc0020 (2022). https://doi.org:doi:10.1126/sciadv.abc0020

90 Parks, S. A., Coop, J. D. & Davis, K. T. Intensifying Fire Season Aridity Portends Ongoing Expansion of Severe Wildfire in Western US Forests. *Global Change Biology* **31**, e70429 (2025). https://doi.org:https://doi.org/10.1111/gcb.70429

91 Gill, A. M. & Zylstra, P. Flammability of Australian forests. *Australian Forestry* **68**, 87-93 (2005). https://doi.org:10.1080/00049158.2005.10674951

92 Canadell, J. G. *et al.* Multi-decadal increase of forest burned area in Australia is linked to climate change. *Nature Communications* **12**, 6921 (2021). https://doi.org:10.1038/s41467-021-27225-4

93 Andela, N. *et al.* A human-driven decline in global burned area. *Science* **356**, 1356-1362 (2017). https://doi.org:doi:10.1126/science.aal4108

94 Zubkova, M., Humber, M. L. & Giglio, L. Is global burned area declining due to cropland expansion? How much do we know based on remotely sensed data? *International Journal of Remote Sensing* **44**, 1132-1150 (2023). https://doi.org:10.1080/01431161.2023.2174389

95 Archibald, S. Managing the human component of fire regimes: lessons from Africa. *Philosophical Transactions of the Royal Society B: Biological Sciences* **371** (2016). https://doi.org:10.1098/rstb.2015.0346

96 Donovan, V. M., Wonkka, C. L. & Twidwell, D. Surging wildfire activity in a grassland biome. *Geophysical Research Letters* **44**, 5986-5993 (2017). https://doi.org:https://doi.org/10.1002/2017GL072901

97 Kolden, C. A., Abatzoglou, J. T., Jones, M. W. & Jain, P. Wildfires in 2024. *Nature Reviews Earth & Environment* **6**, 237-239 (2025). https://doi.org:10.1038/s43017-025-00663-0

98 Chowdhury, S., Hänninen, R., Uppstu, A., Sofiev, M. & Aunan, K. Global health burden from acute exposure to fine particles emitted by fires. *npj Clean Air* **1**, 24 (2025). https://doi.org:10.1038/s44407-025-00024-7

99 Pausas, J. G. & Ribeiro, E. The global fire–productivity relationship. *Global Ecology and Biogeography* **22**, 728-736 (2013). https://doi.org:https://doi.org/10.1111/geb.12043

100 Fisher, R., Legge, S., Catt, G. & Cliff, H. Extensive fires in Australia's northern spinifex deserts – investigating the 2023 'Black Spring' and the influence of indigenous fire management. *International Journal of Wildland Fire* **34**, - (2025). https://doi.org:https://doi.org/10.1071/WF25002

101 Cook, B. I. *et al.* Twenty-First Century Drought Projections in the CMIP6 Forcing Scenarios. *Earth's Future* **8**, e2019EF001461 (2020). https://doi.org:https://doi.org/10.1029/2019EF001461

102 Christian, J. I. *et al.* Global projections of flash drought show increased risk in a warming climate. *Communications Earth & Environment* **4**, 165 (2023). https://doi.org:10.1038/s43247-023-00826-1

103 Jain, P., Castellanos-Acuna, D., Coogan, S. C. P., Abatzoglou, J. T. & Flannigan, M. D. Observed increases in extreme fire weather driven by atmospheric humidity and temperature. *Nature Climate Change* **12**, 63-70 (2022). https://doi.org:10.1038/s41558-021-01224-1

104 Abatzoglou, J. T., Williams, A. P. & Barbero, R. Global Emergence of Anthropogenic Climate Change in Fire Weather Indices. *Geophysical Research Letters* **46**, 326-336 (2019). https://doi.org:https://doi.org/10.1029/2018GL080959

105 Resco de Dios, V. *et al.* A semi-mechanistic model for predicting the moisture content of fine litter. *Agricultural and Forest Meteorology* **203**, 64-73 (2015). https://doi.org:https://doi.org/10.1016/j.agrformet.2015.01.002

106 Fang, Z., Zhang, W., Brandt, M., Abdi, A. M. & Fensholt, R. Globally Increasing Atmospheric Aridity Over the 21st Century. *Earth's Future* **10**, e2022EF003019 (2022). https://doi.org:https://doi.org/10.1029/2022EF003019
107 Hermann, M., Wernli, H. & Röthlisberger, M. Drastic increase in the magnitude of very rare summer-mean vapor pressure deficit extremes. *Nature Communications* **15**, 7022 (2024). https://doi.org:10.1038/s41467-024-51305-w
108 Ellis, T. M., Bowman, D. M. J. S., Jain, P., Flannigan, M. D. & Williamson, G. J. Global increase in wildfire risk due to climate-driven declines in fuel moisture. *Global Change Biology* **28**, 1544-1559 (2022). https://doi.org:https://doi.org/10.1111/gcb.16006
109 Swain, D. L. *et al.* Hydroclimate volatility on a warming Earth. *Nature Reviews Earth & Environment* **6**, 35-50 (2025). https://doi.org:10.1038/s43017-024-00624-z
110 McNorton, J., Moreno, A., Turco, M., Keune, J. & Di Giuseppe, F. Hydroclimatic Rebound Drives Extreme Fire in California's Non-Forested Ecosystems. *Global Change Biology* **31**, e70481 (2025). https://doi.org:https://doi.org/10.1111/gcb.70481
111 Allen, R. J., Gomez, J., Horowitz, L. W. & Shevliakova, E. Enhanced future vegetation growth with elevated carbon dioxide concentrations could increase fire activity. *Communications Earth & Environment* **5**, 54 (2024). https://doi.org:10.1038/s43247-024-01228-7
112 Hersbach, H. *et al.* The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society* **146**, 1999-2049 (2020). https://doi.org:https://doi.org/10.1002/qj.3803
113 Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. FAO Irrigation and drainage paper No. 56. *Rome: Food and Agriculture Organization of the United Nations* **56**, e156 (1998).
114 Palmer, W. C. Meteorological drought. US. *Weather Bureau Res. Paper* **45**, 1-58 (1965).
115 Vitolo, C. *et al.* ERA5-based global meteorological wildfire danger maps. *Scientific Data* **7**, 216 (2020). https://doi.org:10.1038/s41597-020-0554-z
116 Udy, D. G., Vance, T. R., Kiem, A. S., Holbrook, N. J. & Abram, N. Australia's 2019/20 Black Summer fire weather exceptionally rare over the last 2000 years. *Communications Earth & Environment* **5**, 317 (2024). https://doi.org:10.1038/s43247-024-01470-z
117 Turco, M. *et al.* Anthropogenic climate change impacts exacerbate summer forest fires in California. *Proceedings of the National Academy of Sciences* **120**, e2213815120 (2023). https://doi.org:10.1073/pnas.2213815120
118 Abatzoglou, J. T. & Williams, A. P. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences* **113**, 11770-11775 (2016). https://doi.org:doi:10.1073/pnas.1607171113
119 Arno, S. F. & Brown, J. K. Overcoming the paradox in managing wildland fire. *Western Wildlands* **17**, 40–46 (1991).
120 Kreider, M. R. *et al.* Fire suppression makes wildfires more severe and accentuates impacts of climate change and fuel accumulation. *Nature Communications* **15**, 2412 (2024). https://doi.org:10.1038/s41467-024-46702-0
121 Mariani, M. *et al.* Disruption of cultural burning promotes shrub encroachment and unprecedented wildfires. *Frontiers in Ecology and the Environment* **20**, 292-300 (2022). https://doi.org:https://doi.org/10.1002/fee.2395
122 Roos, C. I. *et al.* Native American fire management at an ancient wildland–urban interface in the Southwest United States. *Proceedings of the National Academy of Sciences* **118**, e2018733118 (2021). https://doi.org:10.1073/pnas.2018733118
123 Bliege Bird, R., Codding, B. F., Kauhanen, P. G. & Bird, D. W. Aboriginal hunting buffers climate-driven fire-size variability in Australia's spinifex grasslands. *Proceedings of the National Academy of Sciences* **109**, 10287-10292 (2012). https://doi.org:10.1073/pnas.1204585109

124 Swetnam, T. W. *et al.* Multiscale perspectives of fire, climate and humans in western North America and the Jemez Mountains, USA. *Philosophical Transactions of the Royal Society B: Biological Sciences* **371**, 20150168 (2016). https://doi.org:doi:10.1098/rstb.2015.0168

125 Moreira, F. *et al.* Wildfire management in Mediterranean-type regions: paradigm change needed. *Environmental Research Letters* **15**, 011001 (2020). https://doi.org:10.1088/1748-9326/ab541e

126 Uriarte, M. *et al.* Depopulation of rural landscapes exacerbates fire activity in the western Amazon. *Proceedings of the National Academy of Sciences* **109**, 21546-21550 (2012).

127 Pausas, J. G. & Fernández-Muñoz, S. Fire regime changes in the Western Mediterranean Basin: from fuel-limited to drought-driven fire regime. *Climatic Change* **110**, 215-226 (2012). https://doi.org:10.1007/s10584-011-0060-6

128 Setterfield, S. A., Rossiter-Rachor, N. A., Hutley, L. B., Douglas, M. M. & Williams, R. J. BIODIVERSITY RESEARCH: Turning up the heat: the impacts of Andropogon gayanus (gamba grass) invasion on fire behaviour in northern Australian savannas. *Diversity and Distributions* **16**, 854-861 (2010). https://doi.org:https://doi.org/10.1111/j.1472-4642.2010.00688.x

129 Miller, G., Friedel, M., Adam, P. & Chewings, V. Ecological impacts of buffel grass (Cenchrus ciliaris L.) invasion in central Australia – does field evidence support a fire-invasion feedback? *The Rangeland Journal* **32**, 353-365 (2010). https://doi.org:10.1071/RJ09076

130 Fusco, E. J., Finn, J. T., Balch, J. K., Nagy, R. C. & Bradley, B. A. Invasive grasses increase fire occurrence and frequency across US ecoregions. *Proceedings of the National Academy of Sciences* **116**, 23594-23599 (2019). https://doi.org:doi:10.1073/pnas.1908253116

131 Guo, Y., Wang, J., Ge, Y. & Zhou, C. Global expansion of wildland-urban interface intensifies human exposure to wildfire risk in the 21st century. *Science Advances* **10**, eado9587 (2024). https://doi.org:10.1126/sciadv.ado9587

132 Teymoor Seydi, S. *et al.* Increasing global human exposure to wildland fires despite declining burned area. *Science* **389**, 826-829 (2025). https://doi.org:10.1126/science.adu6408

133 Ellis, T. M., Bowman, D. M. J. S. & Williamson, G. J. Human activity augments lightning ignitions to reshape fire seasonality across all biomes on Earth. *Nature Ecology & Evolution* (2025). https://doi.org:10.1038/s41559-025-02862-w

134 Matt, J. Paradise Redux. *Places Journal* (2024).

135 Giannopoulos, B. *20 charged over Mati wildfires that killed 100 people. URL: https://greekcitytimes.com/2019/03/06/20-charged-over-mati-wildfires-that-killed-100-people/*, 2019).

136 Balch, J. K. *et al.* Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences* **114**, 2946-2951 (2017). https://doi.org:10.1073/pnas.1617394114

137 Tang, W. *et al.* Widespread phytoplankton blooms triggered by 2019–2020 Australian wildfires. *Nature* **597**, 370-375 (2021). https://doi.org:10.1038/s41586-021-03805-8

138 FIRE, C. Damage Inspection (DINS) Data. Accessed on 6 Nov 2025. URL: https://data.ca.gov/dataset/cal-fire-damage-inspection-dins-data. (2025).

139 Lareau, N. P. *et al.* Fire-Generated Tornadic Vortices. *Bulletin of the American Meteorological Society* **103**, E1296-E1320 (2022). https://doi.org:https://doi.org/10.1175/BAMS-D-21-0199.1

140 Lv, Q. *et al.* Increasing severity of large-scale fires prolongs recovery time of forests globally since 2001. *Nature Ecology & Evolution* (2025). https://doi.org:10.1038/s41559-025-02683-x

141 Turner, M. G., Braziunas, K. H., Hansen, W. D. & Harvey, B. J. Short-interval severe fire erodes the resilience of subalpine lodgepole pine forests. *Proceedings of the National Academy of Sciences* **116**, 11319-11328 (2019). https://doi.org:doi:10.1073/pnas.1902841116

142 Le Breton, T. D. *et al.* Megafire-induced interval squeeze threatens vegetation at landscape scales. *Frontiers in Ecology and the Environment* **20**, 327-334 (2022). https://doi.org:https://doi.org/10.1002/fee.2482

143 Enright, N. J., Fontaine, J. B., Bowman, D. M. J. S., Bradstock, R. A. & Williams, R. J. Interval squeeze: altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. *Frontiers in Ecology and the Environment* **13**, 265-272 (2015). https://doi.org:https://doi.org/10.1890/140231

144 Pausas, J. G. & Parr, C. L. Towards an understanding of the evolutionary role of fire in animals. *Evolutionary Ecology* **32**, 113-125 (2018). https://doi.org:10.1007/s10682-018-9927-6

145 Jones, G. M. *et al.* Fire-driven animal evolution in the Pyrocene. *Trends in Ecology & Evolution* https://doi.org:10.1016/j.tree.2023.06.003

146 Nimmo, D. G., Jolly, C. J. & Carthey, A. J. R. Megafire: the Darwinian guillotine? *Australian Zoologist* **42**, 217-222 (2022). https://doi.org:10.7882/az.2022.022

147 Griffiths, A. & Christian, K. The effects of fire on the frillneck lizard (Chlamydosaurus kingii) in northern Australia. *Australian Journal of Ecology* **21**, 386-398 (1996).

148 Keith, D. A. Transcending the disaster paradigm: Understanding persistence of animal populations in fire-prone environments. *Global Change Biology* **28**, 341-342 (2022). https://doi.org:https://doi.org/10.1111/gcb.15925

149 Nimmo, D. G., Carthey, A. J. R., Jolly, C. J. & Blumstein, D. T. Welcome to the Pyrocene: Animal survival in the age of megafire. *Global Change Biology* **27**, 5684-5693 (2021). https://doi.org:https://doi.org/10.1111/gcb.15834

150 Nimmo, D. G., Jolly, C. J. & Carthey, A. J. R. Expanding the scope of fire-driven animal evolution. *Trends in Ecology & Evolution* **38**, 1115-1116 (2023). https://doi.org:10.1016/j.tree.2023.09.005

151 Law, B. S. *et al.* Fire severity and its local extent are key to assessing impacts of Australian mega-fires on koala (Phascolarctos cinereus) density. *Global Ecology and Biogeography* **31**, 714-726 (2022). https://doi.org:https://doi.org/10.1111/geb.13458

152 Eeden, L. v. *et al.* Impacts of the unprecedented 2019-2020 bushfires on Australian animals. WWF-Australia. (2020).

153 Jolly, C. J. *et al.* Animal mortality during fire. *Global Change Biology* **28**, 2053-2065 (2022). https://doi.org:https://doi.org/10.1111/gcb.16044

154 Sanderfoot, O. V. *et al.* A review of the effects of wildfire smoke on the health and behavior of wildlife. *Environmental Research Letters* **16**, 123003 (2021). https://doi.org:10.1088/1748-9326/ac30f6

155 Doherty, T. S., Watchorn, D. J., Miritis, V., Pestell, A. J. L. & Geary, W. L. Cats, foxes and fire: quantitative review reveals that invasive predator activity is most likely to increase shortly after fire. *Fire Ecology* **19**, 22 (2023). https://doi.org:10.1186/s42408-023-00183-6

156 McGregor, H. W., Legge, S., Jones, M. E. & Johnson, C. N. Extraterritorial hunting expeditions to intense fire scars by feral cats. *Scientific Reports* **6**, 22559 (2016). https://doi.org:10.1038/srep22559

157 Doherty, T. S. *et al.* Fire as a driver and mediator of predator–prey interactions. *Biological Reviews* **97**, 1539-1558 (2022). https://doi.org:https://doi.org/10.1111/brv.12853
158 Leahy, L. *et al.* Amplified predation after fire suppresses rodent populations in Australia's tropical savannas. *Wildlife Research* **42**, 705-716 (2016). https://doi.org:https://doi.org/10.1071/WR15011
159 Robinson, N. M. *et al.* Refuges for fauna in fire-prone landscapes: their ecological function and importance. *Journal of Applied Ecology* **50**, 1321-1329 (2013).
160 Meddens, A. J. H. *et al.* Fire Refugia: What Are They, and Why Do They Matter for Global Change? *BioScience* **68**, 944-954 (2018). https://doi.org:10.1093/biosci/biy103
161 Keeley, J. E. & Pausas, J. G. Distinguishing disturbance from perturbations in fire-prone ecosystems. *International Journal of Wildland Fire* **28**, 282-287 (2019). https://doi.org:10.1071/WF18203
162 Xu, H. *et al.* Global patterns and drivers of post-fire vegetation productivity recovery. *Nature Geoscience* **17**, 874-881 (2024). https://doi.org:10.1038/s41561-024-01520-3
163 Pausas, J. G., Keeley, J. E. & Bond, W. J. The role of fire on Earth. *BioScience*, biaf132 (2025). https://doi.org:10.1093/biosci/biaf132
164 Jones, M. W. *et al.* Global rise in forest fire emissions linked to climate change in the extratropics. *Science* **386**, eadl5889 (2024). https://doi.org:10.1126/science.adl5889
165 Aragão, L. E. O. C. *et al.* 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nature Communications* **9**, 536 (2018). https://doi.org:10.1038/s41467-017-02771-y
166 Walker, X. J. *et al.* Increasing wildfires threaten historic carbon sink of boreal forest soils. *Nature* **572**, 520-523 (2019). https://doi.org:10.1038/s41586-019-1474-y
167 Pellegrini, A. F. A. *et al.* Fire effects on the persistence of soil organic matter and long-term carbon storage. *Nature Geoscience* **15**, 5-13 (2022). https://doi.org:10.1038/s41561-021-00867-1
168 Page, S. E. *et al.* The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* **420**, 61-65 (2002). https://doi.org:10.1038/nature01131
169 Harrison, S. P. *et al.* The biomass burning contribution to climate–carbon-cycle feedback. *Earth Syst. Dynam.* **9**, 663-677 (2018). https://doi.org:10.5194/esd-9-663-2018
170 Liu, Z., Ballantyne, A. P. & Cooper, L. A. Biophysical feedback of global forest fires on surface temperature. *Nature Communications* **10**, 214 (2019). https://doi.org:10.1038/s41467-018-08237-z
171 Pereira, P., Francos, M., Brevik, E. C., Ubeda, X. & Bogunovic, I. Post-fire soil management. *Current Opinion in Environmental Science & Health* **5**, 26-32 (2018). https://doi.org:https://doi.org/10.1016/j.coesh.2018.04.002
172 Dahm, C. N., Candelaria-Ley, R. I., Reale, C. S., Reale, J. K. & Van Horn, D. J. Extreme water quality degradation following a catastrophic forest fire. *Freshwater Biology* **60**, 2584-2599 (2015). https://doi.org:https://doi.org/10.1111/fwb.12548
173 Hart, S. C., DeLuca, T. H., Newman, G. S., MacKenzie, M. D. & Boyle, S. I. Post-fire vegetative dynamics as drivers of microbial community structure and function in forest soils. *Forest Ecology and Management* **220**, 166-184 (2005). https://doi.org:https://doi.org/10.1016/j.foreco.2005.08.012
174 Bernath, P., Boone, C. & Crouse, J. Wildfire smoke destroys stratospheric ozone. *Science* **375**, 1292-1295 (2022). https://doi.org:10.1126/science.abm5611
175 Thomas, J. L. *et al.* Quantifying black carbon deposition over the Greenland ice sheet from forest fires in Canada. *Geophysical Research Letters* **44**, 7965-7974 (2017). https://doi.org:https://doi.org/10.1002/2017GL073701

176 Pyne, S. J. *Fire in America: a cultural history of wildland and rural fire*. (University of Washington Press, 2017).
177 Christianson, A. C. *et al.* Wildland fire evacuations in Canada from 1980 to 2021. *International Journal of Wildland Fire* **33**, - (2024). https://doi.org:https://doi.org/10.1071/WF23097
178 Wittwer, G. & Waschik, R. Estimating the economic impacts of the 2017–2019 drought and 2019–2020 bushfires on regional NSW and the rest of Australia. *Australian Journal of Agricultural and Resource Economics* **65**, 918-936 (2021). https://doi.org:https://doi.org/10.1111/1467-8489.12441
179 Wang, D. *et al.* Economic footprint of California wildfires in 2018. *Nature Sustainability* **4**, 252-260 (2021). https://doi.org:10.1038/s41893-020-00646-7
180 Thomas, D., Butry, D., Gilbert, S., Webb, D. & Fung, J. The costs and losses of wildfires. *NIST special publication* **1215**, 1-72 (2017).
181 Rogers, J., Trent, S. & Gillen, A. Dealing with livestock affected by the 2014 bushfires in South Australia: decision-making and recovery. *Australian Journal of Emergency Management, The* **30**, 13-17 (2015).
182 Madhusoodanan, J. Wildfires pose a burning problem for wines and winemakers. *Proceedings of the National Academy of Sciences* **118**, e2113327118 (2021). https://doi.org:10.1073/pnas.2113327118
183 Paglino, E., Raquib, R. V. & Stokes, A. C. Excess Deaths Attributable to the Los Angeles Wildfires From January 5 to February 1, 2025. *JAMA* **334**, 1018-1019 (2025). https://doi.org:10.1001/jama.2025.10556
184 Johnston, F. H., Williamson, G., Borchers-Arriagada, N., Henderson, S. B. & Bowman, D. M. J. S. Climate Change, Landscape Fires, and Human Health: A Global Perspective. *Annual Review of Public Health* **45**, 295-314 (2024). https://doi.org:https://doi.org/10.1146/annurev-publhealth-060222-034131
185 Proctor, C. R., Lee, J., Yu, D., Shah, A. D. & Whelton, A. J. Wildfire caused widespread drinking water distribution network contamination. *AWWA Water Science* **2**, e1183 (2020). https://doi.org:https://doi.org/10.1002/aws2.1183
186 Hohner, A. K., Rhoades, C. C., Wilkerson, P. & Rosario-Ortiz, F. L. Wildfires alter forest watersheds and threaten drinking water quality. *Accounts of chemical research* **52**, 1234-1244 (2019).
187 Bladon, K. D., Emelko, M. B., Silins, U. & Stone, M. Wildfire and the Future of Water Supply. *Environmental Science & Technology* **48**, 8936-8943 (2014). https://doi.org:10.1021/es500130g
188 Lambrou, N., Kolden, C., Loukaitou-Sideris, A. & Li, X. Housing and Economic Recovery as Interdependent Pathways in the Wake of Wildfires. *International Journal of Disaster Risk Reduction*, 105820 (2025).
189 Eriksen, C. & de Vet, E. Untangling insurance, rebuilding, and wellbeing in bushfire recovery. *Geographical Research* **59**, 228-241 (2021).
190 Chang-Richards, Y., Wilkinson, S., Potangaroa, R. & Seville, E. Resource challenges for housing reconstruction: A longitudinal study of the Australian bushfires. *Disaster Prevention and Management: An International Journal* **22**, 172-181 (2013).
191 Mannakkara, S. & Wilkinson, S. Build back better principles for economic recovery: case study of the Victorian bushfires. *Journal of business continuity & emergency planning* **6**, 164-173 (2013).
192 Schulze, S. S., Fischer, E. C., Hamideh, S. & Mahmoud, H. Wildfire impacts on schools and hospitals following the 2018 California Camp Fire. *Natural Hazards* **104**, 901-925 (2020). https://doi.org:10.1007/s11069-020-04197-0
193 Lambrou, N., Kolden, C. & Loukaitou-Sideris, A. Disaster recovery gentrification in post-wildfire landscapes: The case of Paradise, CA. *International Journal of Disaster Risk*

Reduction **118**, 105235 (2025). https://doi.org:https://doi.org/10.1016/j.ijdrr.2025.105235

194 Hamideh, S., Sen, P. & Fischer, E. Wildfire impacts on education and healthcare: Paradise, California, after the Camp Fire. *Natural hazards* **111**, 353-387 (2022).

195 Mockrin, M. H., Stewart, S. I., Radeloff, V. C. & Hammer, R. B. Recovery and adaptation after wildfire on the Colorado Front Range (2010–12). *International Journal of Wildland Fire* **25**, 1144-1155 (2016).

196 McConnell, K. & Braneon, C. V. Post-wildfire neighborhood change: evidence from the 2018 Camp Fire. *Landscape and urban planning* **247**, 104997 (2024).

197 Adachi, J. K. & Li, L. The impact of wildfire on property prices: An analysis of the 2015 Sampson Flat Bushfire in South Australia. *Cities* **136**, 104255 (2023). https://doi.org:https://doi.org/10.1016/j.cities.2023.104255

198 Walls, M. A., Wibbenmeyer, M., Pesek, S. & Liao, Y. P. Insurance availability and affordability under increasing wildfire risk in California. (Resources for the Future, 2022).

199 Mockrin, M. H., Stewart, S. I., Radeloff, V. C., Hammer, R. B. & Alexandre, P. M. Adapting to wildfire: rebuilding after home loss. *Society & Natural Resources* **28**, 839-856 (2015).

200 Thompson, M. P. *et al.* Wildfires have created instability within risk transfer markets. Here's a path forward. *Proceedings of the National Academy of Sciences* **122**, e2530050122 (2025). https://doi.org:10.1073/pnas.2530050122

201 Williamson, B., Weir, J. & Cavanagh, V. (2020). . Strength from perpetual grief: how Aboriginal people experience the bushfire crisis. The Conversation. URL: https://theconversation.com/strength-from-perpetual-grief-how-aboriginal-people-experience-the-bushfire-crisis-129448. (2020).

202 Ambrey, C. L., Fleming, C. M. & Manning, M. The social cost of the Black Saturday bushfires. *Australian Journal of Social Issues* **52**, 298-312 (2017).

203 Brown, M. R. *et al.* Significant PTSD and other mental health effects present 18 months after the Fort McMurray wildfire: findings from 3,070 grades 7–12 students. *Frontiers in psychiatry* **10**, 623 (2019).

204 Bryant, R. A. *et al.* Psychological outcomes following the Victorian Black Saturday bushfires. *Australian & New Zealand Journal of Psychiatry* **48**, 634-643 (2014).

205 Yelland, C. *et al.* Bushfire impact on youth. *Journal of Traumatic Stress: Official Publication of The International Society for Traumatic Stress Studies* **23**, 274-277 (2010).

206 Wong-Parodi, G. When climate change adaptation becomes a "looming threat" to society: Exploring views and responses to California wildfires and public safety power shutoffs. *Energy Research & Social Science* **70**, 101757 (2020).

207 Wagner, S. L. *et al.* Mental Disorders in Firefighters Following Large-Scale Disaster. *Disaster Medicine and Public Health Preparedness* **15**, 504-517 (2021). https://doi.org:10.1017/dmp.2020.61

208 Stanley, I. H., Hom, M. A., Gai, A. R. & Joiner, T. E. Wildland firefighters and suicide risk: Examining the role of social disconnectedness. *Psychiatry Research* **266**, 269-274 (2018). https://doi.org:https://doi.org/10.1016/j.psychres.2018.03.017

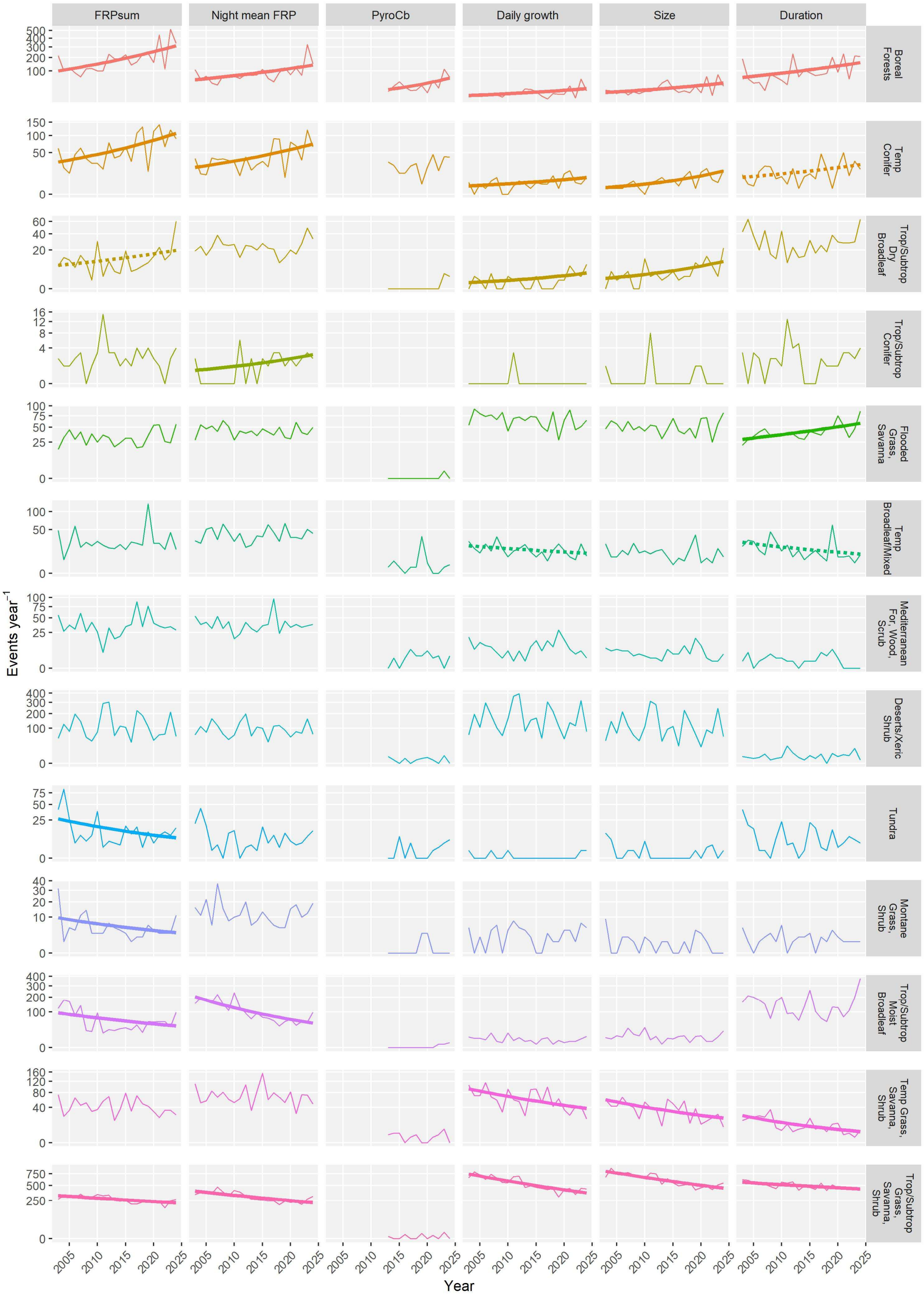
209 Quilcaille, Y., Batibeniz, F., Ribeiro, A. F. S., Padrón, R. S. & Seneviratne, S. I. Fire weather index data under historical and shared socioeconomic pathway projections in the 6th phase of the Coupled Model Intercomparison Project from 1850 to 2100. *Earth Syst. Sci. Data* **15**, 2153-2177 (2023). https://doi.org:10.5194/essd-15-2153-2023

210 Guo, Z. *et al.* Reconstructed global monthly burned area maps from 1901 to 2020. *Earth Syst. Sci. Data* **17**, 3599-3618 (2025). https://doi.org:10.5194/essd-17-3599-2025

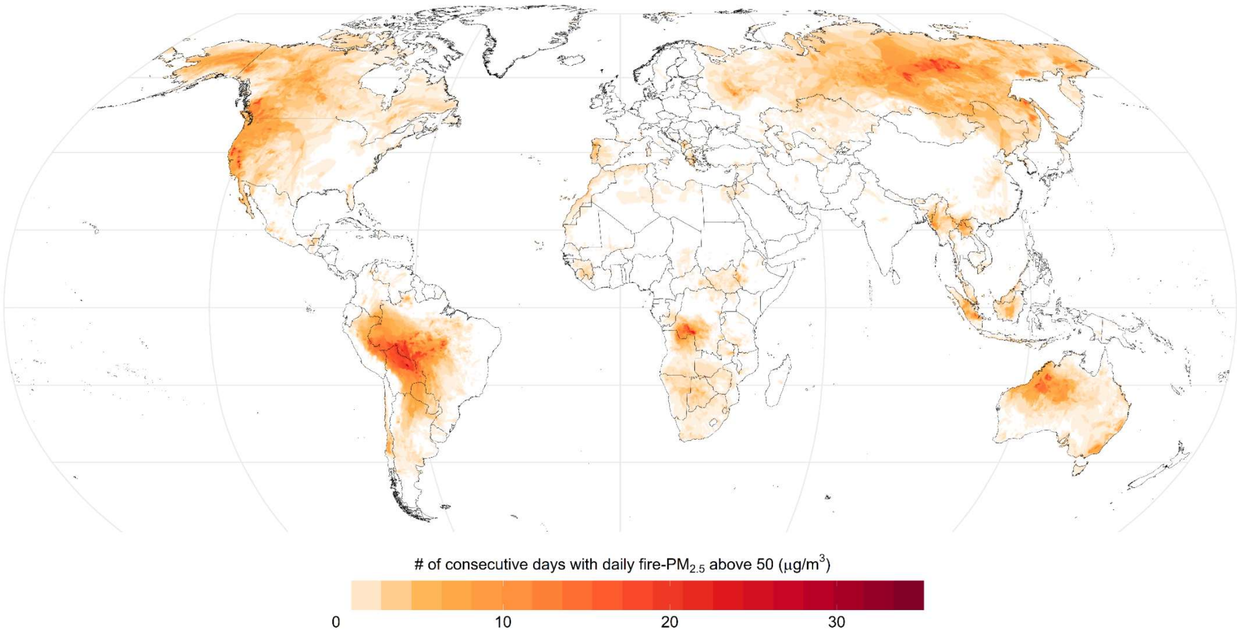
211 Soga, M. & Gaston, K. J. Shifting baseline syndrome: causes, consequences, and implications. *Frontiers in Ecology and the Environment* **16**, 222-230 (2018). https://doi.org:https://doi.org/10.1002/fee.1794

212 Bowman, D. Wildfire science is at a loss for comprehensive data. *Nature* **560**, 7-8 (2018).
213 Kolden, C. A. Wildfires: count lives and homes, not hectares burned. *Nature* (2020).
214 Kelley, D. I. *et al.* State of Wildfires 2024-25. *Earth Syst. Sci. Data Discuss.* **2025**, 1-179 (2025). https://doi.org:10.5194/essd-2025-483
215 Kirchmeier-Young, M. C., Gillett, N. P., Zwiers, F. W., Cannon, A. J. & Anslow, F. S. Attribution of the Influence of Human-Induced Climate Change on an Extreme Fire Season. *Earth's Future* **7**, 2-10 (2019). https://doi.org:https://doi.org/10.1029/2018EF001050
216 Lin, D., Giannico, V., Lafortezza, R., Sanesi, G. & Elia, M. Use of airborne LiDAR to predict fine dead fuel load in Mediterranean forest stands of Southern Europe. *Fire Ecology* **20**, 58 (2024). https://doi.org:10.1186/s42408-024-00287-7
217 Monzón-González, A., Calvo, L., Fernández-García, V. & Fernández-Guisuraga, J. M. Upscaling wildfire consumption using UAV-LiDAR and Sentinel-2 data: a Mediterranean case study. *GIScience & Remote Sensing* **62**, 2555626 (2025). https://doi.org:10.1080/15481603.2025.2555626
218 Boroujeni, S. P. H. *et al.* A comprehensive survey of research towards AI-enabled unmanned aerial systems in pre-, active-, and post-wildfire management. *Information Fusion* **108**, 102369 (2024). https://doi.org:https://doi.org/10.1016/j.inffus.2024.102369
219 Thangavel, K., Spiller, D., Sabatini, R., Marzocca, P. & Esposito, M. Near Real-Time Wildfire Management Using Distributed Satellite System. *IEEE Geoscience and Remote Sensing Letters* **20**, 1-5 (2023). https://doi.org:10.1109/LGRS.2022.3229173
220 Xu, G. & Zhong, X. Real-time wildfire detection and tracking in Australia using geostationary satellite: Himawari-8. *Remote Sensing Letters* **8**, 1052-1061 (2017). https://doi.org:10.1080/2150704X.2017.1350303
221 Sharples, J. Why suppressing all wildfires has made today's megafires worse. *Nature* **644**, 9-9 (2025).
222 Peterson, D. *et al.* INjected Smoke and PYRocumulonimbus Experiment (INSPYRE): White Paper for NASA Earth Venture Suborbital-4 (EVS-4). URL: https://espo.nasa.gov/inspyre/content/INSPYRE_White_Paper_0. (2024).
223 Duane, A. *et al.* Adapting prescribed burns to future climate change in Mediterranean landscapes. *Science of The Total Environment* **677**, 68-83 (2019). https://doi.org:https://doi.org/10.1016/j.scitotenv.2019.04.348
224 Williams, J. W. & Jackson, S. T. Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment* **5**, 475-482 (2007). https://doi.org:https://doi.org/10.1890/070037
225 Cunningham, C. X. *et al.* Pyrogeography in flux: Reorganization of Australian fire regimes in a hotter world. *Global Change Biology* **30**, e17130 (2024). https://doi.org:https://doi.org/10.1111/gcb.17130
226 Center for International Earth Science Information Network - CIESIN - Columbia University. (NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, New York, 2018).
227 Cunningham, C. X., Williamson, G. J. & Bowman, D. M. J. S. Reply to: Increases in the world's most extreme wildfire events probably driven by fire size and simultaneity. *Nature Ecology & Evolution* (2025). https://doi.org:10.1038/s41559-025-02745-0
228 McElhinny, M., Beckers, J. F., Hanes, C., Flannigan, M. & Jain, P. A high-resolution reanalysis of global fire weather from 1979 to 2018 – overwintering the Drought Code. *Earth Syst. Sci. Data* **12**, 1823-1833 (2020). https://doi.org:10.5194/essd-12-1823-2020

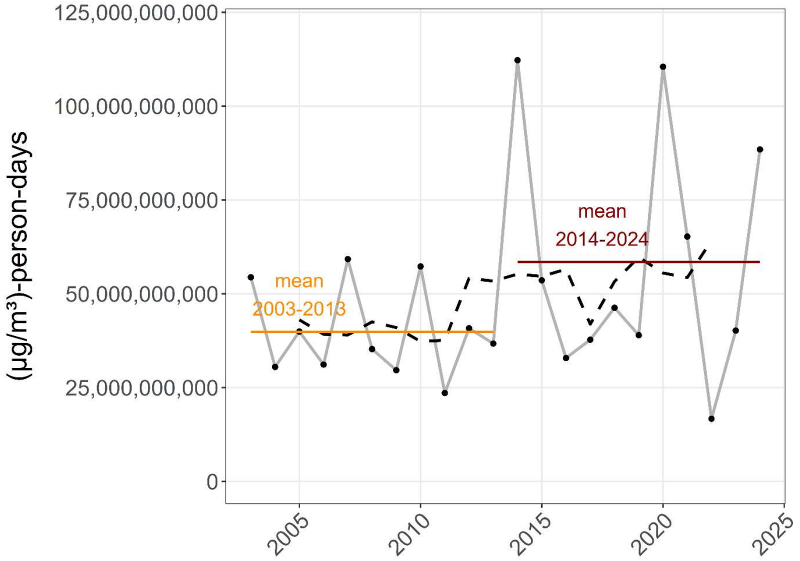
Supplementary Material



Supplementary Figure S1. Temporal trends in extraordinary fire events. *Extraordinary events follow the description in Figure 2 and 3 and Supplementary Text 1.* ***(a)*** *Thin lines show the annual count of extraordinary events. Thick solid lines ($p < 0.05$) and thick dashed lines ($0.05 < p < 0.08$) show statistically significant and marginally significant trends of a generalised linear model (count ~ year; negative binomial distribution). Y-axis is square-root-transformed.*



Supplementary Figure S2. *Number of consecutive days with wildfire derived $PM_{2.5}$ above the 99.9th percentile (~50 μg m^{-3}) from 2000-2024. The most extremely impacted geographic areas include: (1) boreal regions, especially Siberia, (2) temperate forests, especially northwestern North America, (3) tropical forests in South America along the border between Brazil and Bolivia, (4) central Africa, especially the Democratic Republic of Congo, and (5) the monsoon tropical and arid savannas of Western Australia. Data from* [81,226].



Supplementary Figure S3. *Population exposure to extreme daily wildfire sourced $PM_{2.5}$ from 2003-2024, highlighting an increase since 2014. Extreme daily $PM_{2.5}$ was defined by the 99.9th percentile, corresponding to > 50 μg m^{-3}. The dashed line shows the 5-year moving average. Data from* [81,226].

Supplementary Text 1.

This section describes the process involved in the syntheses in Figs 2-5.

Identifying extraordinary fires

To synthesise the distribution and trends in numerous key modes of extraordinary fire, we linked together several publicly available datasets:

(1) The Global Fire Atlas[74] (2003-2024) forms discrete fire events from multiple daily burned area polygons. Each discrete fire event contains information on the start and end dates of the fire as well as its total area. 2003 was selected as the start year because it is the first full year that both the Terra and Aqua satellites were operational.
(2) MODIS daily burned area (MCD64A1[70]) polygons provide polygons of fires at a daily time scale, which can be used to characterise daily growth rate.
(3) MODIS active fires product (MCD14ML[69]) provides up to four daily observations of fire radiative power as point locations reflecting the centre of a 1 km pixel, allowing characterisation of energetics and diel patterns of fire.
(4) A global inventory of pyroCbs (2013-2024)[39]

We spatiotemporally linked the discrete fire events from the Global Fire Atlas to the MODIS burned area and active fires products. For each discrete fire, we calculated the total size, duration, daily growth, mean nighttime fire radiative power, and summed 24-hour fire radiative power, which correlates very closely with fire radiative energy[227].

We then transformed these metrics into percentiles and considered those exceeding the global 99.9th percentile as globally extraordinary, yielding 19,434 fire events in each dimension (except PyroCbs; N = 911). The geographical pattern (Fig 2-3) and temporal trends (Fig 4) across these dimensions were then summarised for the world's biomes[77].

Associations between extraordinary fires and climate

To summarise the associations between extraordinary fires and climate, we linked the extraordinary fire events to metrics of climate (Fig 5). Climate data were acquired from ERA-5 at a 0.25° resolution from 2002-2024. The Fire Weather Index (FWI) was calculated from the Canadian Forest Fire Danger Rating System using the overwintering procedure on the drought code[228] using daily maximum temperature, minimum relative humidity, daily mean wind speed, and daily total precipitation. Further, Palmer Drought Severity Index (PDSI) was calculated at a monthly timescale using monthly total precipitation and reference evapotranspiration (ETo) computed using the Penman-Montieth approach[114]. To facilitate comparison across diverse regions globally, we transformed both FWI and PDSI to local percentile values by pooling data across the full temporal record.

For each type of extraordinary fire event in each biome, we calculated the average PDSI percentiles for the month of fire onset. As FWI data are more dynamic and exhibit day-to-day meteorological variability, we limited compilations of FWI percentiles to dimensions of extraordinary fire that are measured at a daily time scale and therefore have distinct dates (that is, daily energy, pyroCb, and daily growth).