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Human exposure and sensitivity to globally extreme wildfire events

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Extreme wildfires have substantial economic, social and environmental impacts, but there is uncertainty whether such events are inevitable features of the Earth's fire ecology or a legacy of poor management and planning. We identify 478 extreme wildfire events defined as the daily clusters of fire radiative power from MODIS, within a global 10 × 10 km lattice, between 2002 and 2013, which exceeded the 99.997th percentile of over 23 million cases of the ΣFRP 100 km^{-2} in the MODIS record. These events are globally distributed across all flammable biomes, and are strongly associated with extreme fire weather conditions. Extreme wildfire events reported as being economically or socially disastrous ($n = 144$) were concentrated in suburban areas in flammable-forested biomes of the western United States and southeastern Australia, noting potential biases in reporting and the absence of globally comprehensive data of fire disasters. Climate change projections suggest an increase in days conducive to extreme wildfire events by 20 to 50% in these disaster-prone landscapes, with sharper increases in the subtropical Southern Hemisphere and European Mediterranean Basin.

Extreme wildfires have substantial economic, social and environmental impacts, with concern that climate change is increasing their occurrence[1,2]. We show that such events are globally distributed and are associated with highly anomalous fire weather conditions. Our validated global database of extreme wildfires shows that those reported as being economically or socially disastrous are concentrated in suburban areas intermixed with flammable forest in the developed world. The lower occurrence of fire disasters in the Mediterranean compared to the climatically analogous regions in the western United States and southeastern Australia suggest regional land use can substantially reduce the occurrence of fire disasters. Extreme wildfire events are inevitable features of flammable biomes, and climate change is likely to increase their frequency and global occurrence, particularly in subtropical regions of the Southern Hemisphere, and the European Mediterranean Basin and Levant.

Climate change is causing fire seasons to start earlier and finish later[2,3], with an associated trend towards more extreme wildfire events in terms of their geographic extent and duration, intensity, severity, associated suppression costs, and loss of life and property[4]. Determining the relative role of biome, climate change, and past fire management practices in influencing these extreme fire events is essential for effective wildfire policy, and to do this demands using consistent terminology regarding how fires impact the environment[5,6]. The term 'megafire' is widely used to describe such extreme fire events[7,8], but there is currently no agreed-upon operational definition of this concept — which, combined with fragmentary records of fire events and their economic and environmental costs, frustrates global and historical analyses of extreme fire events.

Here, we use energetically extreme landscape fire events as a robust index of the 'extreme wildfire event'. We base our analysis on energy release from the fire radiative power (FRP) MODIS product using daily ΣFRP within a global 10 × 10 km lattice for 4,382 days between 2002 and 2013. We identified over 23 million events and selected the top 500 representing the 99.997th percentile of all the ΣFRP 100 km^{-2} in the MODIS record. We used a systematic verification process to validate that the events were wildfires (Fig. 1), although this approach was unable to differentiate if the cause of the event was multiple individual fires in the same geographic location, or a single fire with multiple high-intensity fire fronts. Accordingly, we describe our unit of analysis as an 'event' rather than as an individual fire. Our approach enables robust analyses given these events are precisely quantified in terms of their energy release, location and timing.

We undertook a systematic web search of media and official reports to determine if these extreme wildfire events were disastrous as defined by criteria designed to capture direct economic, political or social impacts (Fig. 1). Our criteria for extreme wildfire events causing disasters does not account for immediate or long-term impacts on ecosystem goods and services, nor vulnerability to future disasters[9]. We acknowledge that our approach is constrained by the absence of globally comprehensive data on fire disasters, and reliance on media reporting may bias attribution to the developed world. Further, we did not consider the indirect effects of smoke pollution on human health from these extreme wildfire events, a factor known to cause substantial morbidity and occasional mortality[10]. We also categorized the extreme wildfire events into seven groups based on their biological, climatological and societal context (Table 1). The logic of our classification and attribution of extreme fire events is summarized in Fig. 1 and in the Supplementary Information.

Results and discussion

A feature of our analysis is that the extreme wildfire events we have identified have a global distribution, albeit they are generally absent in biomes with a very high rate of landscape fire, such as tropical savanna (Figs 2a and 3). Extreme wildfire events were concentrated in regions with mid-to-high values of fire activity (Fig. 3, grey line), such as the forests of southeastern Australia and the western USA, where wildfire primarily occurs in seasonally dry periods during

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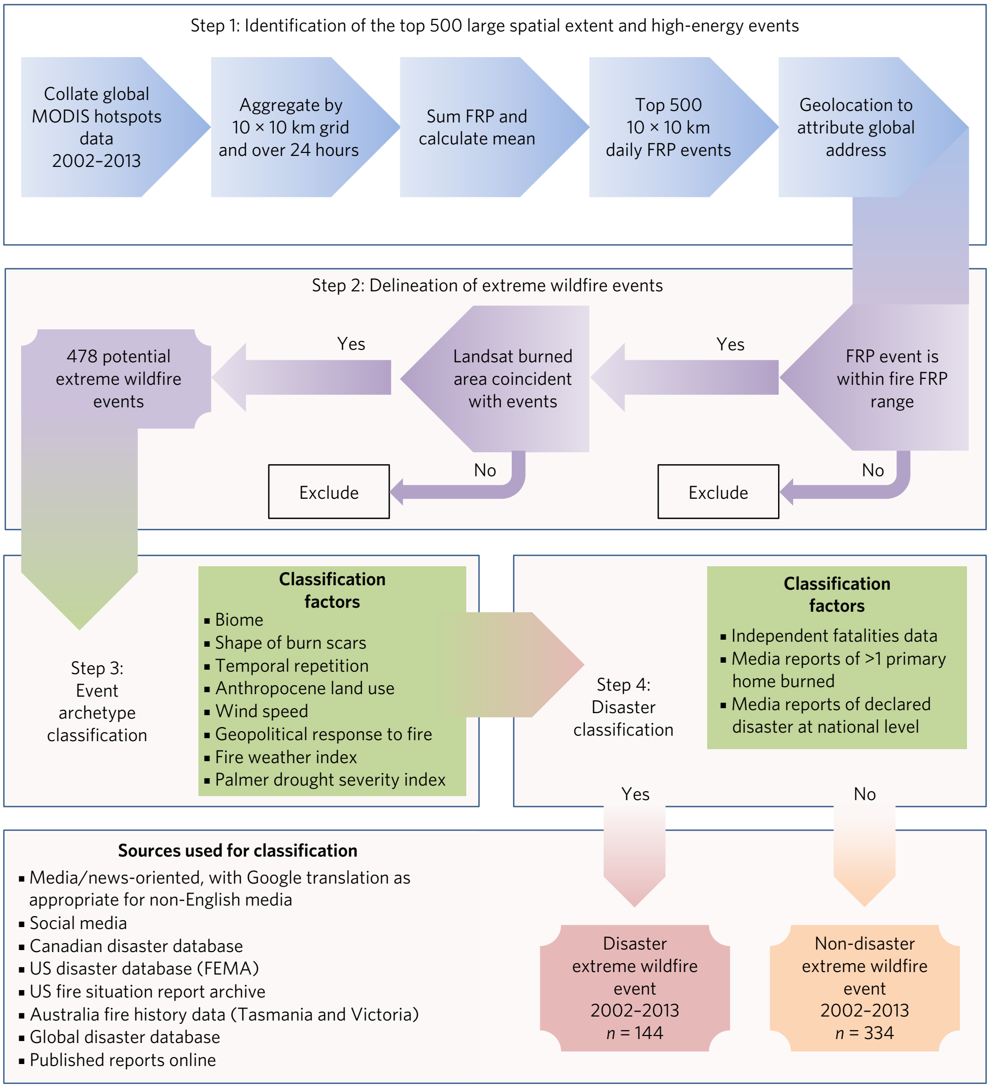

Figure 1 | The methodological workflow used to identify and classify extremely energetic fire events (ΣFRP 100 km^{-2}) in our MODIS record over the period 2002–2013. We use a systematic web search of media reports and official records to discriminate events that either cause substantial economic and social harms or do not, which we operationally define as disasters and non-disasters, respectively. The mean (and range) of FRP between extreme fire events and all events is 35,861 (26,066–91,080) and 118 (3–91,080), respectively.

years with anomalous fire-season aridity (Fig. 2a). Relatively few (4.2%) extreme wildfire events occurred in arid regions, such as central Australia, and these typically occurred in years following anomalously wet conditions (Table 1). These patterns of extreme wildfire events, therefore, are consistent with established pyrogeographic patterns where fire activity is usually limited by the fuel available in low productivity climates (such as arid deserts) and by mesic conditions in highly productive climates[11]. Exceptions to this top–down climate control are the nearly one-tenth (9.8%) of extreme wildfire events that occur in productive tropical landscapes where humans deliberately use fire to clear rainforests and maintain clearings for agricultural uses[12] (Table 1). Around one-quarter of extreme wildfire events were boreal ecosystem fires (26.8%), where they burn sparsely populated areas (Table 1). Disastrous extreme wildfire events are rare in either densely or sparsely populated landscapes (>100 and <1 humans per km^2, respectively) (Fig. 2b), consistent with previous studies that have also shown a bounded relationship between landscape fire and population density[1].

Nearly all (96%) of the disastrous extreme wildfire events were associated with anomalous meteorological conditions such as high temperatures, winds, or fire danger, or anomalous climatic conditions such as drought or abundant antecedent precipitation in arid regions (Table 1 and Fig. 3). Approximately 65% of all extreme wildfire events occurred on days when the fire danger was above the historical 93rd percentile Fire Weather Index (FWI) (Supplementary Fig. 1), and 45% of extreme wildfire events coincided with moderate-to-severe long-term drought, characterized by Palmer Drought Severity Index (PDSI) values less than −2. Strong synoptic or local-scale winds, which cause rapid and uncontrollable fire spread, were associated with about one-third (34.7%) of all the disastrous extreme wildfire events (Table 1).

We expect a continuation of the observed climate-driven trend showing a recent increase in fire danger and an 18.7% mean increase in fire weather season length across land surfaces from 1979–2013[3], given that climate change is unavoidable for the next several decades[13]. The pivotal role of meteorological conditions in driving extreme wildfire events signals increasing global vulnerability to these events with climate change. We applied a pseudo-climate change experiment that combined projected changes in monthly climate to observed daily weather conditions from 2000–2014 while holding all other meteorological variables unchanged to assess future changes in high fire danger (defined as FWI exceeding the historical 93rd

Table 1 | Extreme wildfire event classification.

Extreme wildfire event group	Salient features	Proportion of all extreme wildfire events	Proportion of all disasters	Proportion that are disasters
Boreal/taiga fires	Fires in boreal ecosystems, usually associated with high (>95th percentile) fire danger under extreme drought conditions, in very remote regions and are often very large (as evident from Landsat burn scars). Disasters primarily are officially declared (rather than socioeconomic), often due to evacuation requirements for small native villages in Canada and the USA.	26.8% (*n* = 128)	16.0% (*n* = 23)	18.0%
Wind-driven fires	Across all biomes, and often in concert with high fire danger and drought conditions. Rapid large fire growth and uncontrollable fire behaviour.	25.5% (*n* = 122)	34.7% (*n* = 50)	41.0%
Extreme fire weather	Across all biomes, extreme fire weather conditions (FWI >95th percentile) occur independent of severe drought conditions, antecedent pluvial, or anomalously strong and persistent winds. Many of these events were associated in the media with anomalous fuel accumulations (for example, due to extensive recent bark beetle outbreaks).	17.2% (*n* = 82)	20.8% (*n* = 30)	36.6%
Severe drought	Occur primarily in Australia and western North America temperate zones characterized by severe, long-term drought (PDSI <−3) facilitating vegetation stress.	13.2% (*n* = 63)	21.5% (*n* = 31)	49.2%
Tropics agricultural burning	Occur in tropical regions, well-defined boundaries on Landsat burn scars, area within the boundary burns annually or at regular intervals.	9.8% (*n* = 47)	0.0% (*n* = 0)	0.0%
Antecedent wet year in arid/semi-arid systems	Primarily in deserts and steppe where high antecedent precipitation (long-lead antecedent PDSI one year before fire >4) produced abundant, continuous fuels. Fires are often wind-driven as well, but fuel loading in areas where fuels are otherwise sparse is the distinguishing characteristic.	4.2% (*n* = 20)	3.5% (*n* = 5)	25.0%
Other	Not explicable in terms of biome type or exceptional weather or climate conditions. Some events were described in media reports as occurring in inaccessible, extreme terrain (so they were able to grow to a large size due to ineffective suppression), while others were described as occurring in forests where fire exclusion facilitated heavy fuel load accumulation.	3.3% (*n* = 16)	3.5% (*n* = 5)	31.3%
Total		478	144	30.1%

Allocation of the 478 extreme wildfire events to seven groups of extreme wildfire events based on a subjective classification using climatic, biological and societal criteria: a summary of the salient features of each group is provided. The percentage of all extreme wildfire events, all disasters, and the proportion of disasters amongst each group are also shown.

percentile) by the mid-21st century (2041–2070) (see Methods and Supplementary Fig. 1). Results show an area-weighted 35% increase in the number of days per year of high fire danger across global land surfaces (Fig. 2c). However, these changes exhibit substantial geographic variability, with sharp increases projected for the European Mediterranean Basin and Levant, subtropical Southern Hemisphere (Atlantic coast of Brazil, southern Africa and central east coast of Australia), and southwestern USA and Mexico. Interrogation of projected climate changes in these regions suggests multiple causes for the increasing FWI (Supplementary Fig. 2). In the Mediterranean Basin and the Levant, increases in the frequency of high fire danger days are driven by coincident increases in temperature and declines in humidity during the summer fire season. Changes in the subtropical Southern Hemisphere are driven by reduced spring rainfall. This finding is qualitatively similar to projected changes in the occurrence of very large fires in the USA[13]. An important caveat is that we have not accounted for dynamic feedbacks, which amplify the risks of extreme fires in stressed ecosystems[14,15].

Conclusions

Although extreme wildfire events are inevitable features of the Earth's pyrogeography, not all extreme wildfire events are disasters that cause direct substantial economic or social harms[16]. Land use can substantially reduce the risk of disastrous extreme wildfire events. Flammable landscapes with intermediate human population densities in the western USA and southeastern Australia are particularly affected by extreme wildfire events, but the more densely settled northern Mediterranean Basin with a similar climate to these regions is less disaster prone[1]. Human population growth and climate change is making flammable landscapes increasingly dangerous and costly to manage[16]. Targeted mitigation and adaptation strategies can increase community resilience, leading to sustainable coexistence with environments prone to extreme wildfire events[8].

Methods

Extreme wildfire event definition and validation. We obtained the complete global MODIS active fire hotspot data for the period 2002 to 2013 inclusive from both the Aqua and Terra satellites[17]. One component of the MODIS active fire product, fire radiative power (FRP), is known to scale to smoke plume size and area burnt[18]. We calculated ΣFRP within a global 10 × 10 km lattice (100 km^2 pixels) over a 24-hour period (which captures 4 satellite passes per day) for 4,382 days between 1 January 2002 and 31 December 2013. Initially, we arbitrarily selected 500 clusters with the highest daily ΣFRP. Then we individually assessed these clusters to eliminate those not associated with fire activity through the following two approaches. First, we utilized independent (that is, not MODIS-derived)

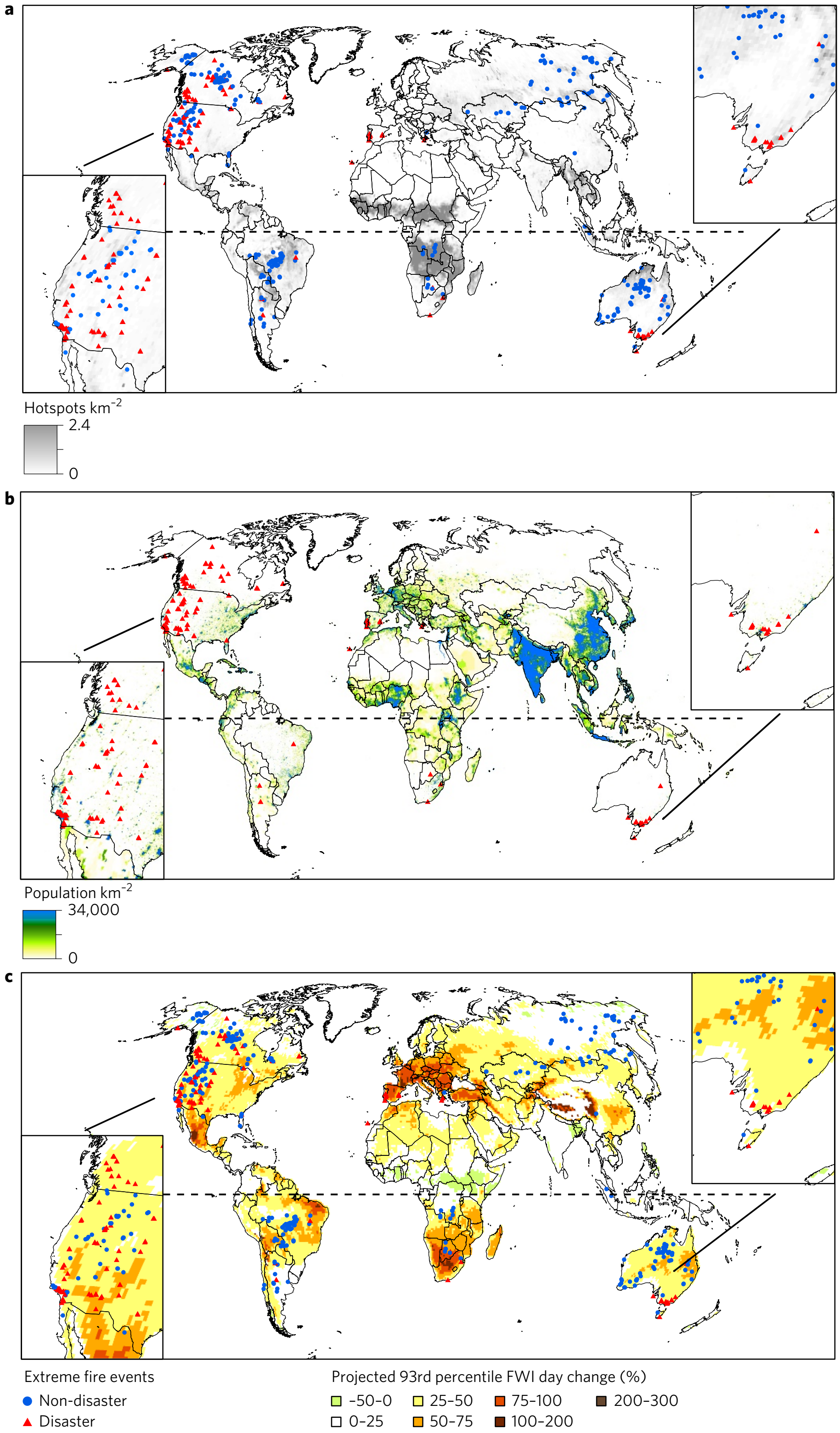

Figure 2 | Global distribution of 478 objectively defined extreme wildfire events, classified by those identified as being disasters (red triangles) or not (blue dots). a–c, Disaster and non-disaster events are overlaid on maps of MODIS hotspot density (**a**), disaster events overlaid on human population density (**b**) and disaster and non-disaster events overlaid on percentage change in number of days exceeding 93rd percentile fire weather index under current conditions to exceedances under projected climate change (**c**) (see Supplementary Fig. 1).

datasets to confirm that each cluster was geospatially and temporally colocated with either a recorded fire event or an observed fire scar. For the USA, Canada and two states in Australia (Victoria and Tasmania), we validated the clusters against large fire databases, including the Monitoring Trends in Burn Severity database (http://www.mtbs.gov), the Canadian National Fire Database (http://cwfis.cfs.nrcan.gc.ca/ha/nfdb) and state databases provided by Tasmanian and Victorian state agencies in Australia. For all other clusters and for any cluster not found in the above databases (which have known errors of omission), we utilized the global

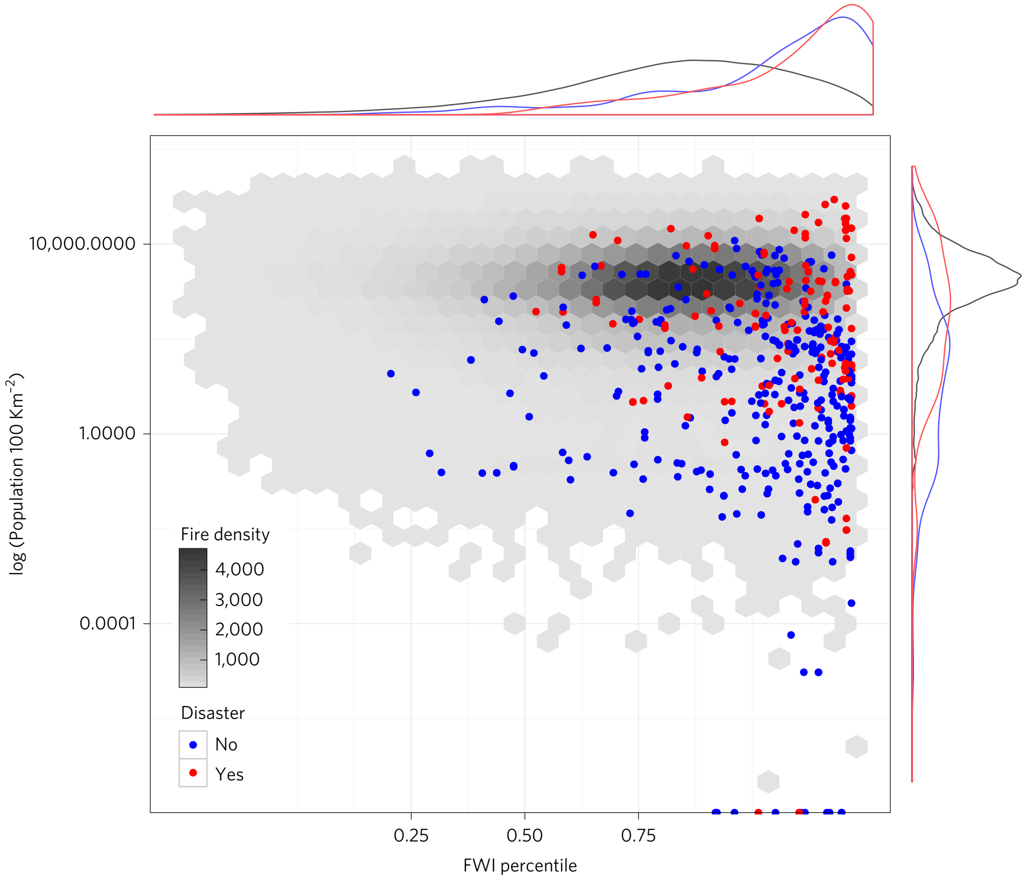

Figure 3 | Plot of all extreme wildfire events classified as disastrous and non-disastrous according to our systematic web search of existing media reports and official records ordinated by a FWI percentile and human population. These extreme wildfire events are overlaid on the density of a 1% sample of all summed daily MODIS FRP cells in the record. The relativized univariate density of Fire Weather Index (FWI) percentiles and population density are shown on the *x* axis and extreme wildfire event axis, respectively, for disaster fires (red), non-disaster fires (blue) and the 1% sample of MODIS FRP cells (grey). Marginal density plots show the distribution of all fires (grey line), non-disastrous extreme wildfire events (blue line) and disastrous extreme wildfire events (red line) plotted against population density and Fire Weather Index. See Fig. 1 for full details on our methodology for identifying and classifying the events. Data source for log scale population: Gridded Population of the World v4[29].

Landsat archive (glovis.usgs.gov) to determine if, for each cluster, a new fire scar was recorded in the archive coincident with the timing of the cluster date.

For the few clusters for which no fire activity was evident, we sought to determine the source of the FRP peak, either via image interpretation in the Landsat archive or through supporting documentation in the media. For all but one non-fire cluster, the FRP cluster was associated with a volcanic eruption that was reported in the media and often visible on the Landsat scene. For one cluster, there is no evidence of either fire or a volcanic eruption; as we were unable to attribute this cluster despite an exhaustive search, we excluded it from the analysis.

Second, we calculated the distributional statistics of the FRP values for each cluster (median, 90th percentile, maximum, mean, and so on) and compared them with observed values from the literature in those ecosystems[19–22] to determine if the FRP values fell within documented ranges for wildfires. This ancillary information was particularly useful in cases where excessive cloud cover obscured post-fire imagery (such as southern coast of South Africa) and where no post-fire imagery was readily available.

We assert that the identified 478 events must satisfy any reasonable definition of an extreme wildfire event as they represent very large areas burned and because their integrated radiant power output exceeds the 99.997th percentile of all the ΣFRP 100 km^{-2} in the MODIS record. Our approach has not identified all extreme wildfire events over the period 2002–2013, and some of the events may be related (for example, the same fire burning across multiple days or multiple cells), but we contend that it provides a representative sample of extreme wildfire events suitable for the identification of global pyrogeographic patterns. Short record length precludes investigation of trends of increasing incidence of extreme wildfire events.

Extreme wildfire event meteorology. Daily data from the European Centre for Medium-Range Weather Forecast global reanalysis[23] at 0.75° spatial resolution were used to calculate FWI values from the Canadian Forest Fire Danger Rating System (CFFDRS), given its widespread use globally[24]. For the projected changes in extreme fire event occurrences, a threshold of 93rd percentile of FWI was used as it corresponded to the inflection of the curve between FWI and the cumulative probability of these events (Supplementary Fig. 1). This threshold discriminated 65% of our confirmed extreme fire events.

Daily maximum temperature and minimum relative humidity were used to accommodate the required inputs of the CFFDRS at 1200 local standard time, as used in previous global calculations of FWI (for example, ref. [3]). We estimated daily minimum relative humidity using daily mean specific humidity and maximum temperature. Percentiles of FWI were calculated relative to the entire calendar year using data from 2000–2014. The Palmer Drought Severity Index (PDSI) was calculated from temperature and potential evapotranspiration from the Climate Research Unit (CRU) time series data version 3.23 at 0.5° spatial resolution from 1900–2014[25]. PDSI was calculated using a standard 150 mm soil water holding capacity and calibrated for the entire 1900–2014 period. We extracted colocated FWI and PDSI for each extreme wildfire event. Concurrent PDSI was defined by the PDSI value for the month coincident with the fire; long-lead antecedent PDSI was defined by the PDSI value 12 months prior to the fire event.

Pseudo-climate change approach. We apply a simple pseudo-climate change perturbation to observed daily meteorological data from 2000–2014 using a delta-method approach[26]. Monthly means of daily 2 m air maximum temperature (*tasmax*) and specific humidity (*huss*), 10 m wind speed (*was*) and precipitation (*pr*) were obtained from 23 global climate models (GCM) participating in the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Supplementary Table 1) for the historical (1850–2005) and future (2006–2099) experiments. For the latter we considered Representative Concentration Pathway (RCP) 8.5. Monthly mean daily minimum relative humidity (*rhsmin*) was estimated using *tasmax*, *huss*, and surface pressure estimated from land surface elevation. We considered projected changes in monthly means for these variables between the observational period (2000–2014) and the mid twenty-first century (2041–2070) from GCM output regridded to the same 0.75° resolution as the ERA-Interim reanalysis data. The multi-model mean signal was applied additively to daily ERA-Interim data from 2000–2014 for *tasmax*, *rhsmin* and *was*, whereas a multiplier was used for daily *pr*. Projected seasonal changes in these variables are shown in Supplementary Fig. 2. This approach preserves the variability of observed climate data across all time scales between the resulting pseudo-climate change experiment and the observational record. However, the approach does not account for changes in variability (such as the frequency of dry days) or sub-GCM grid-scale changes in climate under anthropogenic climate change[27,28].

Extreme wildfire event classification. We classified each extreme wildfire event into an archetype using a set of fuzzy classification criteria, using a single factor according to priorities listed; however, for many events, several factors occurred simultaneously (for example, drought and extreme fire danger). Events that were observed to be deforestation and maintenance of agricultural fields were classified as 'tropics agricultural burning'. This classification does not necessarily include all agricultural burns in the dataset, but rather, only those that we were confident (through image interpretation) were regular agricultural or deforestation burns. Remaining events for which the daily mean wind speed was >6 ms^{-1} were classified as 'wind-driven fires'. Remaining events occurring in the boreal/taiga biome were classified as 'boreal/taiga fires'. Remaining events for which PDSI 12 months prior to the fire exceeded 4.0 and the event occurred in an arid or semi-arid biome were classified as 'antecedent wet conditions'. Remaining events for which concurrent PDSI was lower than −3.0 were classified as 'droughts'. Remaining events for which the FWI was greater than the 95th percentile for that location were classified as 'extreme fire danger events'. We reviewed each of these classifications in the context of both the Landsat imagery (i.e., the shape of the fire scar) and the media reports to identify whether additional information about the event suggested that our primary classification was not appropriate. For example, many of the events had wind speeds that did not exceed our >6 ms^{-1} threshold, but local information and media reports suggested that winds were reported as the primary driver of fire growth. This occurred in many places where local factors, such as topography, can create strong sustained mesoscale winds that may not be reflected at the scale of the reanalysis data. For example, we knew that several of the events were primarily the product of mesoscale Santa Ana wind events in southern California, USA, even though the large-scale, synoptic wind speed was less than our 6 ms^{-1} threshold; these events were re-classified as 'wind-driven'. Other events were those for which we could not find evidence to classify them into one of our other categories. It is possible that these events were wind-driven, or agricultural ignitions, or would fall into one of our archetype categories, but we could not identify an obvious archetype. Several of these (occurring in the USA) were uniquely described in media and fire reports as being the product of steep, complex terrain and over-dense forests stemming from fire suppression policies in fire-adapted biomes.

Extreme wildfire event disaster attribution. In order to determine whether each extreme wildfire event qualified as a disaster, we first defined the criteria for disasters. While many definitions of extreme wildfire events or wildfire disasters draw from the economic impacts, there is no consistent global database that reports socioeconomic fire impacts or even costs of suppression, and many governments around the world purposely keep this information publicly unavailable. Instead, we defined disasters as meeting one of three criteria that are widely reported in the news and social media for nearly every country. These were:

1. The fire caused fatalities (either to firefighters or civilians),
2. The fire consumed primary homes, or
3. The fire was officially declared a disaster by a national government. This criterion primarily applied to fires in USA, Canada and Australia, which have easily accessible national fire disaster records.

We used national databases of declared disasters, the US Situation Report and ICS-209 archives, news media, social media and internet search engine capabilities to determine if a given extreme wildfire event met at least one of the three criteria above; those that did were identified as disasters in our database.

Data availability. The datasets generated during the current study are available from the corresponding author on request.

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Author contributions

D.M.J.S.B. conceived the study and directed the project, G.J.W. conducted the MODIS data analysis and aggregation; C.A.K. and A.M.S.S. undertook the extreme fire event validation; J.T.A. undertook the climate analyses and M.A.C. contributed to the study design. All authors wrote the paper.

Additional information

Supplementary information is available for this paper.

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Competing interests

The authors declare no competing financial interests.