# Vegetation fires in the Anthropocene

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Abstract | Vegetation fires are an essential component of the Earth system but can also cause substantial economic losses, severe air pollution, human mortality and environmental damage. Contemporary fire regimes are increasingly impacted by human activities and climate change, but, owing to the complex fire–human–climate interactions and incomplete historical or long-term datasets, it is difficult to detect and project fire-regime trajectories. In this Review, we describe recent global and regional trends in fire activity and examine projections for fire regimes in the near future. Although there are large uncertainties, it is likely that the economic and environmental impacts of vegetation fires will worsen as a result of anthropogenic climate change. These effects will be particularly prominent in flammable forests in populated temperate zones, the sparsely inhabited flammable boreal zone and fire-sensitive tropical rainforests, and will contribute to greenhouse gas emissions. The impacts of increased fire activity can be mitigated through effective stewardship of fire regimes, which should be achieved through evidence-based fire management that incorporates indigenous and local knowledge, combined with planning and design of natural and urban landscapes. Increasing transdisciplinary research is needed to fully understand how Anthropocene fire regimes are changing and how humans must adapt.

**Biomass**
Non-fossilized organic matter, including living and dead phytomass, organic soils, and animal remains and excrement.

Vegetation fires — also referred to as wildland fires, wildfires, landscape fires, bushfires, biomass burning, forest fires, scrub fires, crop fires and grass fires — are unique Earth-system disturbances that affect the coupled biosphere, hydrosphere, geosphere, cryosphere and atmosphere[1,2] (FIG. 1). For example, during burning, large quantities of water vapour, $CO_2$, $CH_4$, $N_2O$ and aerosols are released, modifying the radiative balance of the Earth[3]; aerosols reduce transmission of solar energy to the land surface, while greenhouse gases trap solar radiation[4]. Extremely intense fires can also can trigger the development of pyrocumulonimbus storms, injecting aerosols into the stratosphere, where they can be transported globally, impacting radiation budgets[5]. Pyrocumulonimbus storms further facilitate extreme fire behaviour by encouraging lightning ground strikes, which ignite new fires[6], presenting a positive feedback. The high concentration of black carbon[4] (soot) in smoke similarly acts to influence the Earth system and future fire activity, whereby the prevention of precipitation coalescence inhibits rain cloud formation[7]. The atmospheric transport and subsequent fallout of soot in the cryosphere additionally reduces albedo and increases snow and ice melt[8,9].

Fire has been a natural feature of the Earth system for the last 420 million years[3]. Strong self-reinforcing interactions between climate, vegetation and fire occurrence have led to distinct ‘fire regimes’, defined by the temporal frequency, spatial extent and pattern, characteristic behaviour and environmental effects of vegetation fires[10]. Organisms have evolved specialized strategies to resist, promote or recover from fire disturbance. Some plant species have life histories tied to specific fire regimes, such as fire-stimulated flowering, post-fire seed release from aerial seed-banks and smoke-triggered seed germination[11]. This specialization means that any departure from the prevailing fire regime, such as fire exclusion or increasing frequency and intensity, can result in population declines or local extinction[12]. For example, woody plant species that exclusively regenerate from seed (obligate seeders) experience regeneration failure if fires become too frequent for seedling growth and maturation[13].

The evolution of fire-wielding hominins around one million years ago introduced much more complexity into the timing, location, extent and behaviour of vegetation fires[14]. For example, hunter-gatherers managed natural resources with fire, attracting herbivores to freshly burned areas[15–17]. Pre-industrial agriculturalists further used fire to clear land and burn crop debris[18]. Furthermore, contemporary humans shape fire regimes by suppressing natural ignitions, as well as modifying landscapes and fuel loads through controlled burns (prescribed fires), land clearing, urbanization, cultivation of non-native plants and animal husbandry[19]. Humans also accidently or maliciously set fires that

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**Key points**

- Vegetation fires are an ancient and essential component of the Earth system, and have shaped the evolution of plants, animals and biogeochemical processes. There are discernible global geographic and temporal patterns of fire activity reflecting the interplay of climate, vegetation and ignitions.
- Anthropogenic influences on fire activity have become more pronounced since the late eighteenth century, reflecting the effects of industrialization and climate change, land clearance, human population growth, replacement of indigenous and traditional fire management, and the subsequent development of large-scale firefighting and fuels management in the twentieth century.
- The human settlement and infrastructure embedded in flammable vegetation contributes to economically disastrous fires.
- Large and frequent fires in boreal and tropical forests have the potential to cause terrestrial carbon stores to become major greenhouse gas sources, amplifying climate change.
- Detecting and predicting changes in fire activity is difficult due to relatively brief fire records, bioregional variability and human involvement. To understand how Anthropocene fire regimes are changing, and how humans must adapt, researchers from biological sciences, physical sciences and humanities and fire-management practitioners must work together.

become uncontrollable (thus, becoming wildfires) and sometimes economically destructive and fatal (fire disasters)[20]. Globally, very few vegetated environments are unaffected by human fire use[21].

Past climate change is known to have influenced the extent, frequency and intensity of vegetation fires by affecting vegetation patterns, fuel abundance, and seasonal and interannual drought[22]. Currently, anthropogenic climate change is altering precipitation patterns and increasing temperatures, resulting in more frequent extreme vegetation-fire events[23–25]. In recent years, for example, there have been increasing media reports of major fire disasters: the wildfires in Chile in 2017, Portugal in 2018, California in 2018 and Australia in 2019–2020 are prominent examples. Such fires have major economic impacts, affecting life, property and human health[26–29], thus, it is important to consider contemporary and future trends in fire activity to inform adaptation and mitigation policies. For instance, the 2019–2020 Australian Black Summer is likely the nation's most costly natural disaster, costing over AUD $100 billion[30], whilst California in the USA saw an estimated USD $40 billion(NatCatSERVICE) in structure losses alone in a dozen major wildfires in 2017–2018. Importantly, these fire disasters are not simply due to climate factors but also the modification of landscapes during the Anthropocene[31,32].

In this Review, we describe how human–environmental interaction shapes fire activity from the viewpoint of pyrogeography[33]. The characteristics of global vegetation fires are outlined, followed by a synthesis of current trends and future projections in fire activity. The effects of changing fire regimes and pathways for adaptation are subsequently discussed, ending with the consideration of adaptation measures and future research priorities.

## Contemporary fire regimes

Vegetation fires burn an annual global average of 400–500 million hectares (Mha)[34,35], with fire patterns driven by the interplay between climate, weather, vegetation type, ignition and anthropogenic fire management[36–38] (FIG. 2). Broadly, fire activity has a unimodal relationship with primary productivity[39–42]. Regions with intermediate levels of primary productivity, such as tropical savannah, burn at a very high frequency (approximately 1–5 years), owing to abundant fuel (vegetation), reliable dry seasons and ample natural and anthropogenic ignitions[43]. In contrast, in rainforest environments that have high primary productivity, fire is naturally rare (on the timescale of millennia)[44], limited to climatic periods when fuel is dry enough to burn, although anthropogenic deforestation fires are an annual occurrence[45] (FIG. 2). In high-biomass boreal and temperate forests, the return time of fires varies between decade and century scales, and is largely controlled by extreme fire weather, ignitions and vegetation cycles[46]. Notably, arid regions are climatically conducive to fires but have a limited capacity to burn due to low primary productivity[47]. However, fire activity in these regions can increase when fuel becomes available, for instance, following interannual wet periods or non-native grass invasions[48].

Vegetation fires are an important source of greenhouse gases, particularly CO$_2$ (REF.[49]). Global mean carbon emissions due to fire were approximately 2.2 Pg per year from 1997 to 2016, about 22% of contemporary global annual carbon emissions from fossil fuel combustion. Of fire-related emissions, about 65% are due to savannah and grassland fires, reflecting the high frequency of burning in these environments, and 10% from temperate and boreal forest fires[50]. Approximately 20% are associated with clearing tropical rainforest for pasture, plantations and agriculture, with the remainder associated with agricultural waste burning[50]. Although emissions from flammable vegetation can be balanced by sequestration during post-fire vegetative recovery, emissions from fires associated with permanent deforestation or combustion of organic deposits such as peatlands[51,52] are net sources of carbon to the atmosphere. Similarly, rapid climate change and increased forest fires could make carbon sinks (forest vegetation and soil) become carbon sources[53].

***Global trends in fire activity.*** Despite increased reporting of fire disasters[54], such as the Australian 2019–2020 bushfire crisis, it is unclear if these disasters are evidence of increasing global fire activity related to climate change[55]. The uncertainty is partially because historical records of fire activity, even for simple metrics like area burned, are short and available for only a few nations[55]. Prehistorical fire records, which are essential to understanding the fire history of infrequently burned vegetation, rely on palaeoecological proxies such as dendrochronology and analysis of sedimentary charcoal[19,56–60]. These proxies, unfortunately, do not directly scale to key components of fire regimes, such as frequency or geographic extent of fires, and there are few regions, such as the western USA, with a large number of high-resolution records that extend into the prehistorical period[60,61].

Satellite imagery is currently used routinely to monitor fire activity but only became available in the 1970s[62]. This period is much shorter than the natural fire-return interval of many forested biomes and could fail to capture infrequent cyclical events, such as the intense droughts

**Pyrocumulonimbus**
Intense convective thunderstorms that develop above highly energetic wildfires, which can reach the stratosphere and create localized weather, including rain, hail, lightning and pyro-tornadoes.

**Fire regimes**
Characteristic syndrome of landscape fire with respect to behaviour, frequency, seasonality, geographic scale and pattern, with predictable biological responses and environmental effects.

**Regenerate**
The process of plant recovery following fire damage, either from seeds stored in the soil or vegetatively from specialized tissues located in roots, stems and branches.

**Ignitions**
Sufficient energy to initiate combustion of plant biomass, and can be natural, such as from lightning, or directly set by humans either deliberately, accidentally or indirectly.

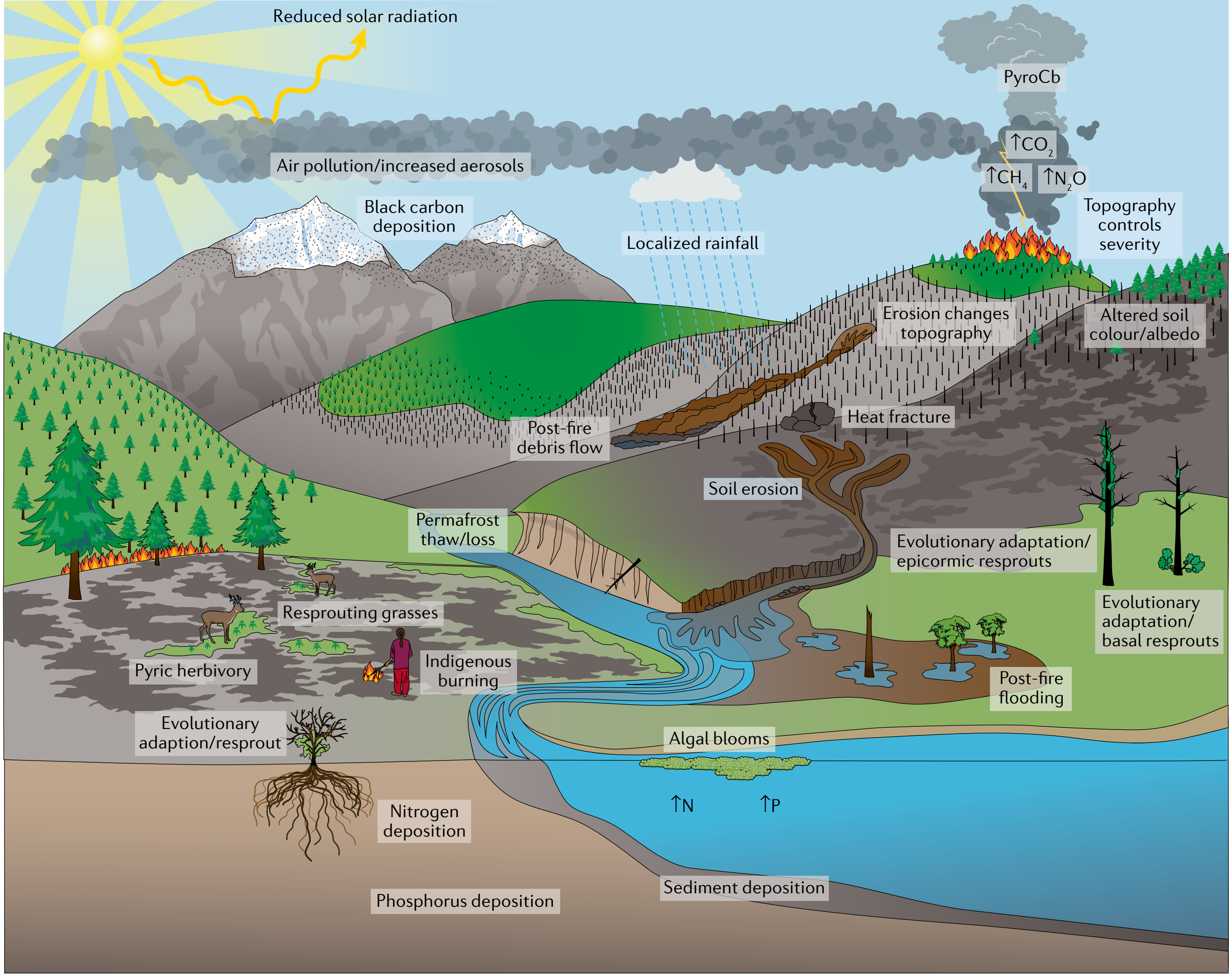

Fig. 1 | **Vegetation fire in the Earth system.** Landscape perspective of the multiple factors that influence, interact with and are impacted by vegetation fire. Fires have numerous direct and indirect affects that impact the biosphere (including vegetation cover), geosphere (including soil erosion), hydrosphere (including fluvial sediment and nutrient transport), cryosphere (including soot fallout and changed albedo) and atmosphere (including smoke pollution). PyroCb, pyrocumulonimbus.

and floods that control fuel availability[63]. Moreover, early satellite observations are spatially coarse and have imperfect coverage[64], with reliable coverage only available since the turn of this century. More uncertainty in global trends arises because of the substantial variation in fire activity amongst biomes, which demands regional rather than global analyses. As fire disasters are often associated with much smaller burned areas than fires in remote areas, metrics other than burned area need to be incorporated into analyses[23,65]. Particularly important are estimates of fire intensity, which provides a measure of the energy released from the fires, and fire severity, which is an estimate of the environmental impacts of the fires, such as degree of canopy damage[66]. Despite these observational limitations, there is an emerging picture of changes in global fire activity, which emphasizes the importance of regional-scale variation, climate change and anthropogenic drivers.

From 1979 to 2013, an average increase of 18.7% in fire-weather-season length has been documented across global burnable lands, with a doubling by long fire-weather seasons across most of the Earth's flammable biomes[67] (FIG. 3). Extreme fire-weather conditions, alongside drought and fuel dryness, are associated with extreme fire events[23]. However, the MODIS burned area record[68] indicates that, between 1998 and 2015, the area burned by vegetation fires globally declined by around 25%, from over 500 Mha to less than 400 Mha annually[69]. The largest decreases in area burned occurred in African and South American tropical savannahs and Asian semi-arid grasslands (FIG. 3a,b), and were caused by ongoing land-cover conversion, leading to a more fragmented and less flammable landscape[69]. A decline greater than the global average of area burned was also detected in western Australian desert, a change known to be associated with interannual drought cycles and the absence

Extreme vegetation-fire events
Extreme fire events are characterized by some combination of the following: anomalous fire behaviour, involving extremely high energy releases, very rapid rate of spread, very large flame heights; massive emission of smoke and greenhouse gas pollution; prolonged duration of fires, enormous geographical scale of burned areas, or both; fires causing unusually adverse biological, atmospheric or geomorphological effects.

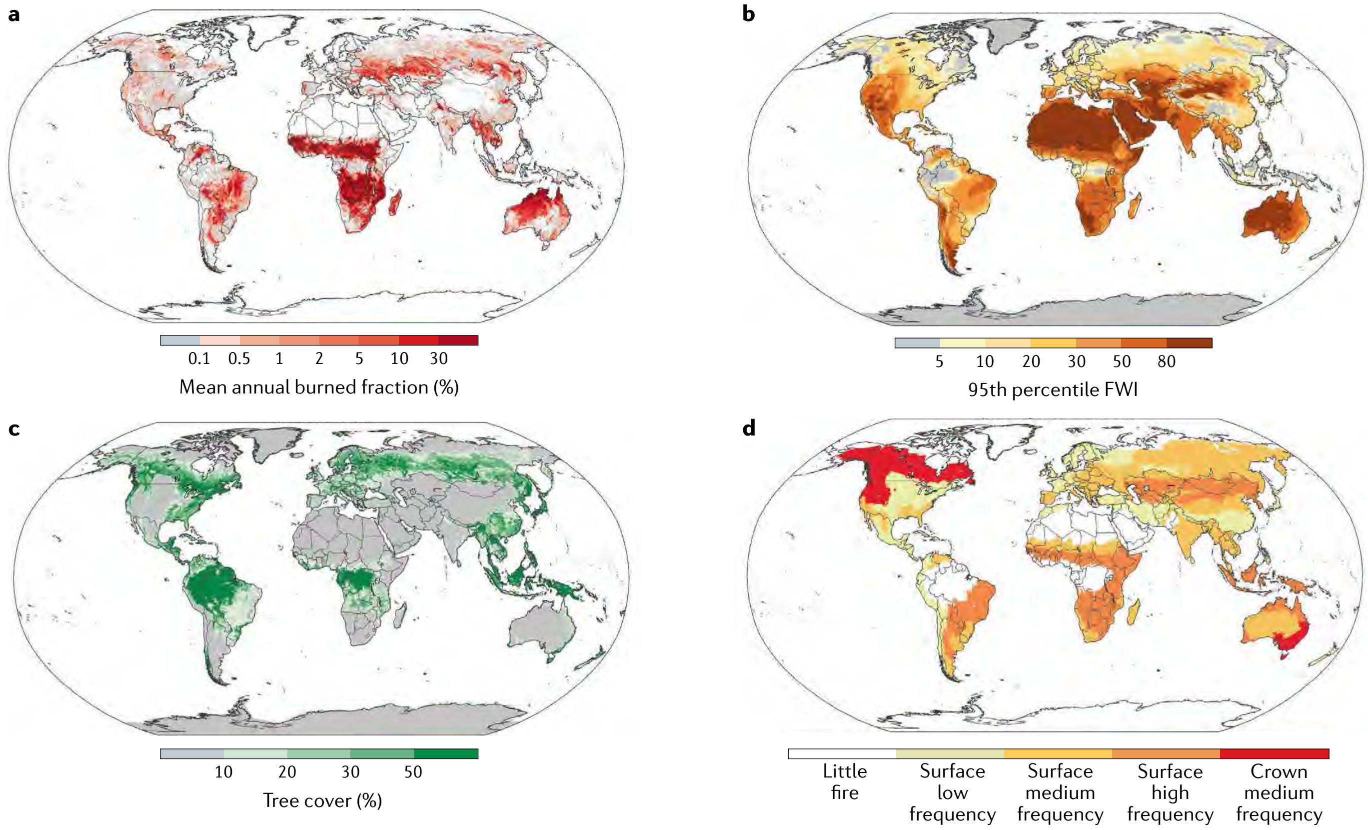

Fig. 2 | **Global patterns of fire and vegetation. a** | Mean annual burned fraction from 2001 to 2018, based on MODIS burned area[34]. **b** | 95th percentile of the Fire Weather Index (FWI) from the Canadian Forest Fire Danger Rating System derived from ERA5 (REF.[224]), where the 95th percentile is calculated from data pooled over the entire calendar year. Higher values represent an increased potential for fire. **c** | Tree cover from MODIS[225]. **d** | Broad spatial pattern of five types of fire regime[38]: little (or no) fire; surface low frequency; surface medium frequency; surface high frequency; and crown medium frequency. Fire activity and regimes are controlled by the interaction of biomass and climate, as well as human and natural ignitions.

of Aboriginal fire management[70,71]. These contrasting trends highlight why a sole focus on area burned does not adequately capture trends in the changing risk of highly economically and economically destructive fire events[65].

***Regional trends in fire activity.*** Regional analyses are essential to reconstruct contemporary fire-activity trends. The most well-studied regions are the western USA (FIG. 3c) and boreal Canada (FIG. 3d), owing to their comparatively high density of researchers, abundant natural archives (lake sediments and fire scars) that record past fires and reliable official fire records since the early twentieth century. Sedimentary charcoal records in the western USA show that, over the last 3,000 years, fire activity was primarily controlled by temperature and drought[60]. During the nineteenth century, however, fire regime became increasingly anthropogenically driven as human population in the region increased and indigenous fire practices waned[72], and fire activity peaked subsequently mid to late century. Active fire suppression decoupled the fire activity–climate relationships and created a historic landscape ‘fire deficit’ in the twentieth century. Since ~1980, though, warmer, drier summers and earlier spring snowmelt[73,74] have increased the area burned from vegetation fires, despite sustained investment in industrialized firefighting[75] (FIG. 3c). For example, between 1972 and 2018, there has been a 405% increase in total burned area in California[76], and decadal burned area from 2003 to 2012 increased by 1,200% in forests of the western USA, compared with 1973–1982 (REF.[77]).

In the Canadian boreal forest, fire frequency and extent has generally increased in response to higher regional temperatures[46,78], longer fire seasons[79] and drier fuels[80] (FIG. 3d). Annual average burned-area in Canada has almost tripled since 1959 from 1 million ha to 2.8 million ha[81]. Drier and hotter fire seasons also increase the probability of lightning ignitions, causing a rise in the number of large fires in western Canada[81,82]. Lightning-caused fires are responsible for 90% of the burned area in Canada, and the number of lightning-caused fires has increased significantly especially over western Canada, resulting in increasing burned area, as burned area by human-caused fires has been decreasing[81]. The combination of drought and vegetation fire has also led to a net increase in greenhouse gas emissions, both directly through the combustion of forest biomass and soil carbon stocks (such as in peatlands) mainly in the form of $CO_2$ (REFS[51,83]) and indirectly by causing permafrost thaw and changing thermokarst hydrology, where the relative emissions of $CH_4$ could increase[84,85].

Anthropocene
The geologically novel planetary state resulting from human activities, although the start date of the state is debated.

Pyrogeography
The holistic study of fire on Earth achieved by combining and synthesizing knowledge and methods from the sciences and humanities.

Dendrochronology
Analysis of growth rings in the trunks of suitable tree species can enable reconstruction of past environmental conditions, resolved to annual or seasonal scales.

Fire intensity
The amount of energy released per unit time from a fire front.

Fire severity
A measure of the biological impact of fires, routinely assessed by the degree of canopy or understory defoliation and foliage consumption.

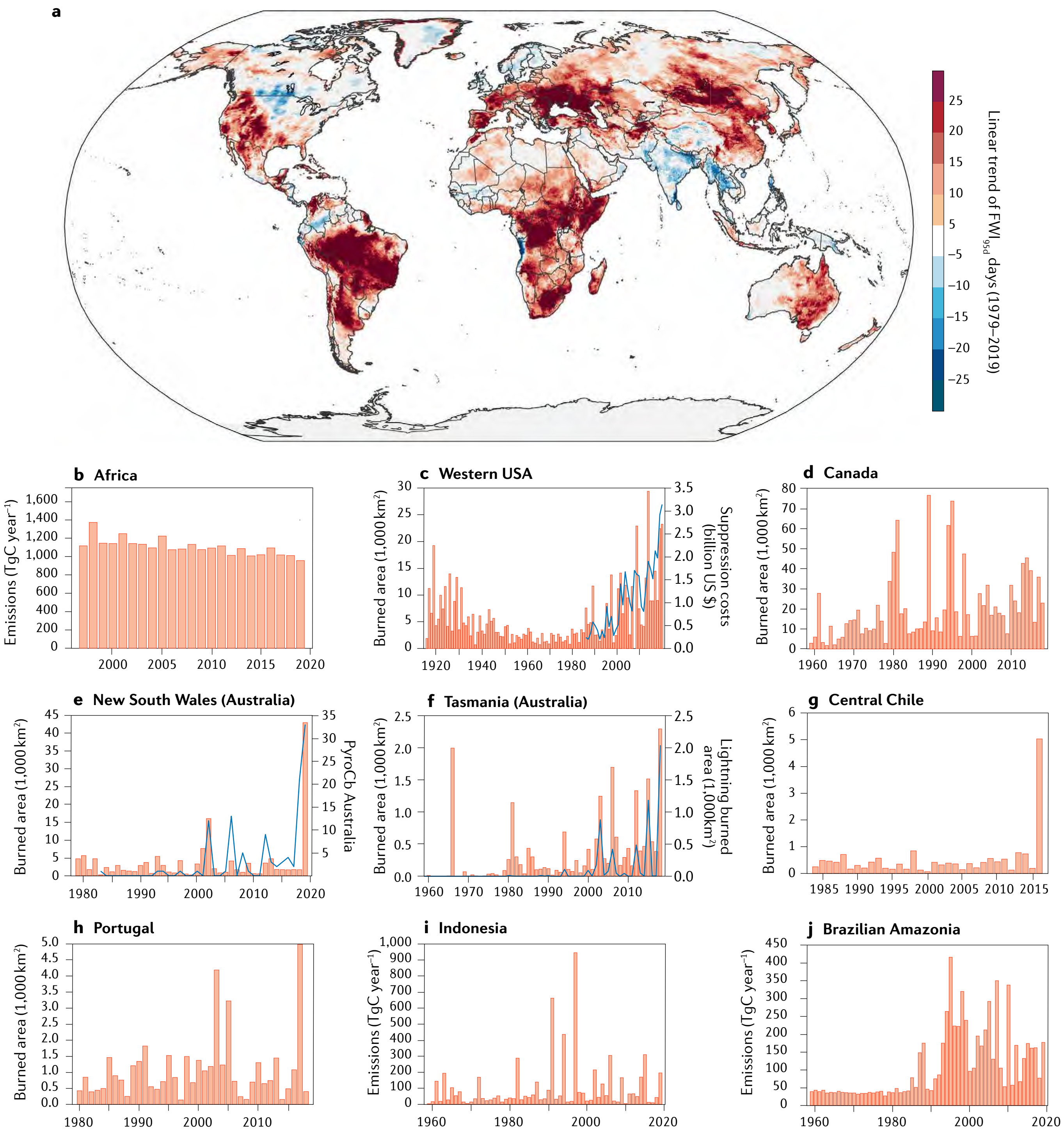

Fig. 3 | **Trends in vegetation-fire activity.** **a** | Linear trends in the number of days per year where the Fire Weather Index (FWI) from ERA5 (REF.[224]) exceeded the local 95th percentile over the period 1979–2019. **b** | Annual fire emissions over Africa (1997–2019)[42]. **c** | Burned area in contiguous Western USA, 103 °W to the Pacific (1916–2018) and non-inflation-adjusted US federal fire-suppression costs (blue line). Burned area based on historical reconstruction from 1916 to 1984 (REF.[226]), Monitoring Trends in Burn Severity (MTBS) data for 1984–2017 (REF.[227]) and MODIS for 2018 (REF.[34]). Data were bias corrected using periods of overlap to the reference MTBS record (1984–2003 for reconstruction and MTBS, and 2001–2017 for MODIS). **d** | Burned area in Canada (1959–2018)[81]. **e** | Burned area in New South Wales, Australia (1979–1980 through 2019–2020 fire seasons) and number of pyrocumulonimbus[24] (PyroCb) in Australia (blue line). **f** | Burned area in Tasmania, Australia (1979–1980 through 2018–2019 fire seasons) resulting from all ignitions (unknown and lightning)[91]. Blue line represents burned area from fires with lightning ignitions. **g** | Burned area in central Chile (1984–1985 through 2016–2017 fire seasons)[95]. **h** | Burned area in Portugal (1980–2018)[228] (2018 estimated using MODIS data[34]). **i** | Fire emissions in Indonesia (1960–2019)[99]. **j** | Fire emissions from Brazilian Amazonia (1960–2019)[99].

In Australia, it is difficult to disaggregate the influences of climate change from the effects of the cessation of >45,000 years of Aboriginal hunter-gatherer fire management following European colonization in the early nineteenth century[86,87]. However, the effect of climate change is becoming apparent in the increasing numbers of extreme fire events[24,88,89]. For instance, analysis of historical satellite imagery has demonstrated an increasing trend in pyrocumulonimbus occurrence[24,90], with 35 storms in the 2019–2020 fire season, thereby, doubling the known Australian records of these extreme fires (FIG. 3e). In the western Tasmanian wilderness, the number of lightning-ignited fires and the area burned as a result has also sharply increased since 1980–1985, from burning an average of around 100 ha annually[91] to over 200,000 ha in 2019 (FIG. 3f), including rarely burned and fire-sensitive Gondwanan rainforests[92]. Most recently, a globally anomalous 2019–2020 fire season in Australia burned over 5 million ha of *Eucalyptus* forests[93] and has been linked with anthropogenic climate change[93,94].

Similar to the 2019–2020 fires in Australia, the 2017 Chilean fires were the largest fires on record for that nation, burning over 5,000 km$^2$ (FIG. 3g), and were associated with anomalous fire-weather conditions related to drought and high temperatures[95]. However, large expanses of highly flammable, densely stocked monocultures of *Pinus* and *Eucalyptus* plantations contributed to the scale and intensities of the Chilean fires[95], a situation that also occurred in the 2018 Portugal fires[96] (FIG. 3h). These cases highlight the importance of factors other than (or in addition to) climate change, such as vegetation changes related to agriculture or invasive species, in fire regime change. For instance, the spread of *Bromus tectorum* (cheatgrass) across the semi-arid, intermountain western USA has facilitated the replacement of a low-frequency, mixed-severity shrubland fire regime with a high-frequency, high-severity grassland fire regime[97]. The introduction of *Andropogon gayanus* (gamba grass) to tropical eucalypt savannah surrounding Darwin in northern Australia has similarly led to the replacement of near-annual high-frequency, low-intensity fires with high-intensity fires, driving the savannah on a trajectory towards a treeless state[98]. Moreover, tropical deforestation fires have remained relatively constant over the last 30 years after increasing during the 1980s in line with increased deforestation[99,100], despite climate change. Instead, an important feature of tropical deforestation fires is the strong interannual variation in step with drought cycles, such as those caused by the El Niño–Southern Oscillation[101,102] (FIG. 3i,j).

In many regions, it is apparent that fire seasons are lengthening and becoming more extreme, and lightning ignitions are increasing, contributing to economically destructive fire events. Yet, simple attribution of these increases to climate change is challenging because there are specific factors, including anthropogenic ones, that shape regional fire activity. These factors can increase the risk of extreme events in some cases, and, in other cases, cause a decline in area burned, highlighting the need to consider and to record more indices than simply area burned.

## Future fire regimes

Fire-activity prediction is a rapidly changing field informed by improved resolution of climate-change projections, increased capacity of numerical models and deeper understanding of the climate drivers of fire activity. Over the last 40 years, a variety of modelling approaches have been applied both globally and regionally to discern likely changes in fire activity owing to anthropogenic climate change. TABLE 1 summarizes the rapid-response review on projected changes in fire activity by geographical region based on papers published since the Fifth Assessment Report of the Intergovernmental Panel on Climate Change[103], augmented with additional key papers discussed here. Overall, there is general agreement amongst the studies that the frequency or severity of fire weather, fire-season length, burned area and fire occurrence are increasing with future climate change. Although some regions are suggested to have no change or decreases in fire activity, particularly in regions with substantial human influence, none of the papers support a widespread decrease in fire risk (TABLE 1). However, it should be noted that there is a limited number of studies for Africa and Asia.

The strong association between anomalous fire weather and extreme fire behaviour suggests that anthropogenic climate change will impact future fire regimes[23,104], including in those regions already vulnerable to fire disasters, such as the western USA, Mediterranean and southern Australia[23]. A global analysis using 17 global climate models, and highlighted regionally in TABLE 1, suggests there will be a large increase in the occurrence of extreme fire weather for much of the globe, with some of the largest increases the Mediterranean and the Amazon[105]. For instance, the number of days exceeding the 95th percentile of the Fire Weather Index is projected to increase almost 130% for the Mediterranean to just under 40% for Alaska when global mean temperatures reach 2 °C above pre-industrial levels relative to contemporary conditions. There is also evidence that increasing atmospheric temperatures will lead to more lightning activity[82,106], further adding to fire activity in ignition-limited landscapes. Such changes in environmental factors will be confounded by changes in anthropogenic factors, including human-settlement patterns and land use (such as cropland and pasture), in many areas of the globe that tend to reduce fire activity[107,108].

Approaches have been used to model future changes in global fire activity ranging from the use of process-based coupled Earth System Models to statistical approaches. For example, Kloster and Lasslop[108] examined future changes in global burned area across a set of Earth System Models with integrated fire–vegetation dynamics that were forced with future changes in climate and land use. The models generally showed increases in global burned area, albeit with substantial uncertainty, with some models showing a 58% increase by the end of the twenty-first century under stronger warming scenarios. Statistical-modelling efforts include Moritz et al.[109], who used environmental-niche modelling to project changes in global fire activity. They found heterogeneous changes in fire activity with general

Table 1 | **Summary of selected global, biome and regional studies on future changes in fire indicators**

| Geographic domain | Projected change in Fire Weather Index days >95th percentile (%) | Fire activity indicator | Projected change of fire activity indicator | Ref. |
|---|---|---|---|---|
| ***Global studies*** | | | | |
| Global | – | Fire weather | Increase | 210 |
| Global[a] | – | Fire weather | Increase | 105 |
| Global | – | Fire weather | Increase | 104 |
| Global | – | Fire weather | No change | 211 |
| Global[a] | – | Fire weather | Increase | 212 |
| Global[a] | – | Burned area | Mixed | 108 |
| Global | – | Burned area | Mixed | 107 |
| Global | – | Fire activity | Increase | 213 |
| Global[a] | – | Fire activity | Mixed | 109 |
| ***Biome studies*** | | | | |
| Mediterranean biome[a] — Europe/S. America/N. America/Australia/Africa | – | Fire activity | Mixed | 118 |
| Boreal biome — Central Russia/W. Canada | – | Fire weather | Increase | 214 |
| ***Regional studies*** | | | | |
| Europe — Mediterranean | +23.5 (129%) | Burned area | Increase | 116 |
| Europe — Mediterranean | | Fire activity | Mixed | 118 |
| Europe — France | | Fire weather | Increase | 116 |
| South America — Amazon | +15.5 (84.9%) | Fire activity | Increase | 215 |
| South America — Amazon | | Burned area | Increase | 216 |
| Australia — Southeast Australia | +9 (49.3%) | Fire weather | Increase | 217 |
| Australia — Southeast Australia | | Fire weather | Increase | 90 |
| Australia[a] — Southeast Australia | | Fire weather | Increase | 24 |
| Australia — Tasmania | | Fire weather | Increase | 218 |
| North America[a] — Western USA | +10.2 (55.9%) | Burned area | Mixed | 115 |
| North America[a] — Western USA | | Burned area | Increase | 114 |
| North America[a] — Western USA | | Fire activity | Increase | 112 |
| North America — California | | Fire impacts | Increase | 219 |
| North America — California | | Fire Weather | Increase | 220 |
| North America[a] — Central Rocky Mountains | | Burned area | Increase | 113 |
| North America — Canada/boreal forest | +9.2 (50.4%) | Fire weather | Increase | 111 |
| North America — Canada/boreal forest | | Fire weather | Increase | 221 |
| North America — Canada/boreal forest | | Fire weather | Increase | 111 |
| North America — Canada/boreal forest | | Burned area | Increase | 221 |
| North America[a] — Canada/boreal forest | | Burned area | Increase | 46 |
| North America — Alaska/Western Canada | | Burned Area | Increase | 78 |
| North America[a] — Alaska | +7.1 (38.9%) | Burned area | Increase | 222 |

Studies include those from Jones et al.[223] and other studies discussed in the text (marked with[a]). Regional studies are summarized by continent and sub-geographic region or country. The primary fire indicator as either fire activity (such as fire occurrence), burned area, fire weather (such as fire danger) or fire impacts, as well as the primary direction of change, is highlighted for each study. For some macroscale regions, also reported are the projected changes in the number of days per year the Fire Weather Index from the Canadian Forest Fire Danger Rating System exceeds the 95th percentile corresponding with global mean temperatures 2 °C above pre-industrial levels versus 1981–2010 (REF.[105]). We summarize the median change calculated from 17 climate models, with the percent change from the 1981–2010 baseline in parentheses.

increases in mid-to-high latitudes and declines in the subtropics.

Regional-scale studies of future fire regimes, largely focused on North America and Mediterranean Europe, have examined changes in metrics such as fire-season length[110], extreme fire weather[111] and burned area. The boreal zone of Canada, for instance, is expected to experience a doubling of burned area by the end of the century, increasing to 5 Mha year$^{-1}$ (REF.[46]). Similarly, more extreme fire weather is projected to favour more

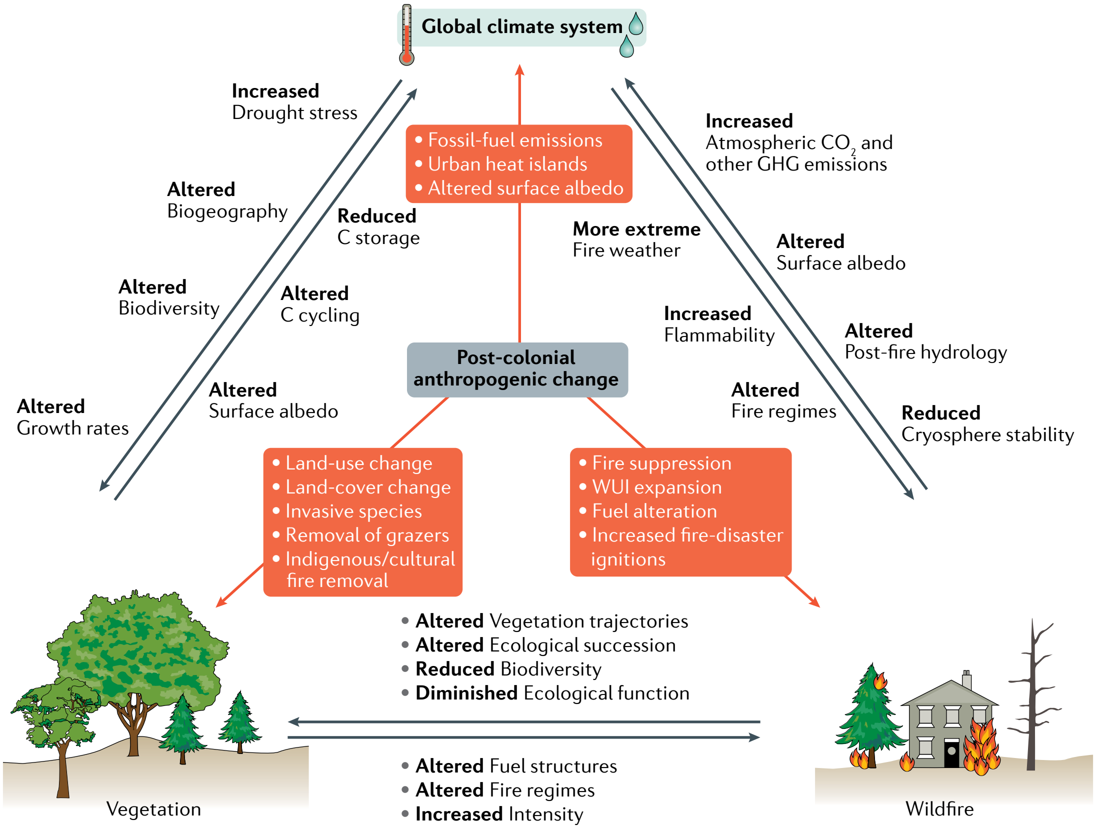

Fig. 4 | **Relationships and feedbacks between climate, fire and vegetation.** Linkages and feedbacks between the global climate system, wildfire and vegetation could drive future fire activity in the Anthropocene. The effects of post-colonial anthropogenic changes to global climate, vegetation and wildfire are shown on the red lines.The consequences of these effects on global climate, vegetation and wildfire are shown on the black lines. These interrelationships highlight the complexity of fire in the Earth system and the sensitivity to climate change, underscoring the challenge in predicting future fire regimes. GHG, greenhouse gas; WUI, wildland–urban interface.

very large fires for the western USA[112] and, in concert with reduced spring snowpack and drier fuels during the summer, will lead to a substantial increase in burned area for montane forests[113]. Process-based land-surface models also show substantial continued increases in burned area over the twenty-first century across forested portions of the western USA[114]. Projected changes in burned area that incorporate direct flammability controls on fire activity and the indirect effects of fuel productivity, however, show more mixed changes across western USA due to heterogeneity in climate, vegetation and land use[115]. For example, semi-arid shrub and grasslands that warm further and undergo aridification will see reduced fire due to biomass limitations.

In Mediterranean Europe, projections suggest a 40–100% increase in burned area with a 1.5 °C to 3 °C warming[116], despite recent investment and expansion of fire-suppression efforts that have led to a reduction in fire-activity since the 1980s[117]. In some Mediterranean ecosystems in Europe, though, burned area could decline if climate-change-associated aridification increases fuel limitation[118]. However, such changes in fire regimes modelled using space-for-time substitutions are predicated on vegetation equilibrium with climate; trailing-edge disequilibrium of vegetation under transient climatic changes could delay realization of reduced fire activity in some landscapes.

***Projection uncertainty.*** Although the projections reviewed here support that there will be increased fire activity in the future, these projections carry large uncertainties due to the feedbacks between different aspects of the Earth system and the difficulty in representing human behaviour in models. For example, one approach to predicting future changes in fire regimes is to explore the statistical association between current and projected climate variables and area burned[40,109]. However, the relationship between vegetation fire and vegetation is likely to change in the future due to dynamic feedbacks, which is not accounted for using statistical associations[108,119,120]. Another approach, process-based mechanistic modelling, incorporates the complex interplay of climate, $CO_2$, vegetation and fire, and, sometimes, impacts of land-use change and change in ignitions[121]. These factors could amplify, dampen or negate one another[63] (FIG. 4). Some global modelling results suggest that the effects of climate change will substantially overwrite human influences on fire regimes[122], for instance, by limiting the effectiveness of fire suppression[123,124]. This conclusion, though, hinges on realistic representations of anthropogenic factors, which are particularly difficult to capture when modelling

Aridification
A process where climate change can lead to sustained regional drying with concomitant changes in vegetation, fire regimes and geomorphological processes.

Climate refugia
A landscape setting with an atypical climate where species poorly adapted to ambient environmental conditions are able to persist, for example, a cloudy mountain top.

Fire refugia
A landscape setting that limits the egress of fires, enabling species poorly adapted to ambient fire regimes to persist, such as a deep ravine.

future fire activity, as it relies on plausible scenarios of economic development and numerical relationships between human population density and ignitions, fire suppression and fuel availability[37,107,108,121]. Thus, regional-scale models are likely to have higher veracity than global models because biophysical and socio-ecological controls of fire activity have distinct geographic patterns[37,109]. Regardless, comparative analyses of different model outputs and observed patterns in area burned show that one of the greatest barriers to modelling future fire regimes concerns anthropogenic factors[125].

There is also uncertainty in fire-regime predictions due to the complexity of climate–fire–vegetation interactions and feedbacks[120]. For example, in some regions, climate change could increase the abundance of plants with low flammability, such as through the replacement of coniferous forests by deciduous broadleaf forests in boreal landscapes[119]. Feedbacks between logging, deforestation, fire, drought and climate change could lead to the replacement of Amazon rainforests with flammable grasslands[126]. Elevated atmospheric $CO_2$ concentrations increase carbon assimilation and improve plant water-use efficiency[127], potentially altering the balance of grass and woody plants in tropical savannahs. In this case, shrub and tree invasion reduces the amount of grass that fuels vegetation fires, thus, decreasing flammability[107,128]. However, climate-change-enhanced drought could negate any effects of carbon fertilization and enhanced water-use efficiency, maintaining or increasing flammability. Most modelling results suggest that negative fire-vegetation feedbacks would limit the extent of projected increases in burned area, based on fire weather alone[116,129], although possible positive fire–vegetation feedbacks, such as invasive annual grass cycles and increased productivity with climate change, could counteract the negative feedbacks[130].

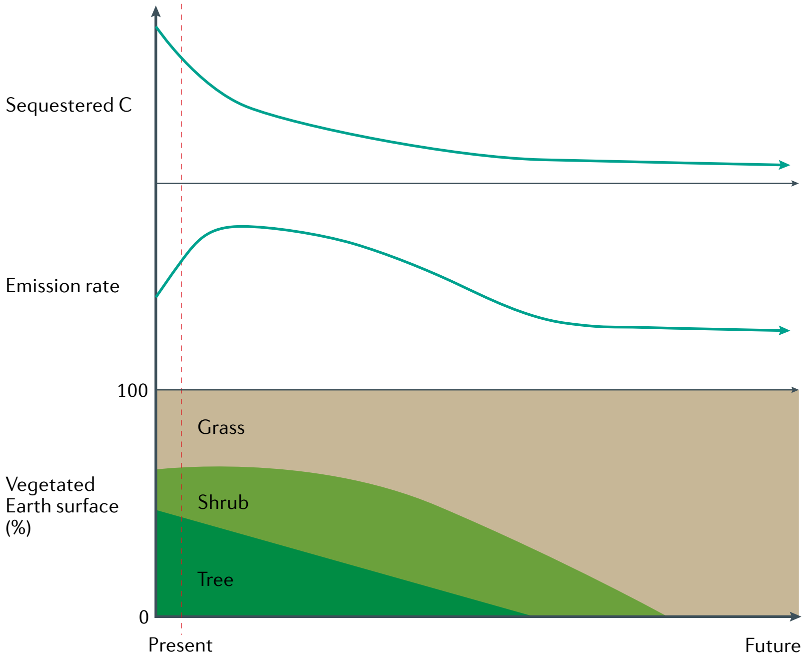

Fig. 5 | **Conversion of infrequently burned forest to a frequently burned, treeless state.** Conversion is associated with declines in carbon storage (sequestered C, top panel) and annual global fire-induced emissions (emission rate, middle panel), assuming that both above-ground and below-ground carbon are altered. In most forested systems, particularly in temperate and boreal ecosystems, much of the sequestered carbon is in litter and soil organic layers and the roots, which can become substantial sources of carbon emissions when burned, especially by repeated fires[188,203,229].

In theory, interactions between climate change, vegetation and fire could drive a runaway feedback process in which entire landscapes are transformed as fire frequency increases with worsening fire weather, and dry, hot conditions[13,131] limit vegetation regeneration (FIG. 5). Ecosystems currently located on the fringe of a bioclimatic niche (such as lower tree line forests) and vegetation persisting in climate refugia or fire refugia are particularly vulnerable to transformative fire regimes[92,131,132]. Landscape-wide conversions from slow-growing, infrequently burned forests to frequently burned grassland and shrublands are possible (FIG. 5), which depletes soil carbon stores, as in regrowth forests in the conifer forests in the western USA[133] and in Indonesia[134]. This feedback process is most likely self-correcting because fire regimes will shift from being flammability-limited to fuel-limited with increasing reduced productivity[40,42,133]. According to this scenario, burned area will eventually decrease and, consequently, more complex vegetation structure will develop, as has been observed in grasslands of the US Great Plains, where the intentional exclusion of fire has facilitated woody tree and shrub expansion[135].

Another key area of uncertainty in future fire-regime predictions is the range of variability and frequency of extreme fire events, and there is a lack of research projecting these events and linking them to cascading consequences, such as post-fire floods, large-scale erosion and debris flows that alter hydrology and topography, and development of pyrocumulonimbus[136]. The paucity of projections is partially due to the substantial challenges and uncertainties inherent in coupling interdisciplinary models, as well as the increased level of uncertainty and error at the extremes[90,137,138]. Fire, and its interactions, remains poorly represented Earth-system models, and their performance struggles with non-analogue, rapidly changing future climates[139]. Thus, predicting 'black swan' extreme fire events — which, by definition, have no historical precedent, such as the protracted, enormous and severe Australian 2019–2020 fires — seriously challenge the capacity of Earth-system-model projections. The Australian fires represented a unique constellation of historically anomalous prolonged drought, the unusual conjunction of interannual climate modes (an intense positive-phase Indian Ocean Dipole and negative-phase Southern Annular Mode) that resulted in a prolonged fire weather, localized lightning storms and human ignitions than ignited the fires, combined with intentionally set fires and direct firefighting designed to stop the fires[140]. Clearly, capturing such specific combinations of climate events and human agency to predict such an extreme event is beyond the capacities of current predictive models of future fire activity[139].

## Adapting to fire in the Anthropocene

Fire regimes in the Anthropocene require adaptation and effective management to promote environmental sustainability and reduce greenhouse gas emissions[33,141].

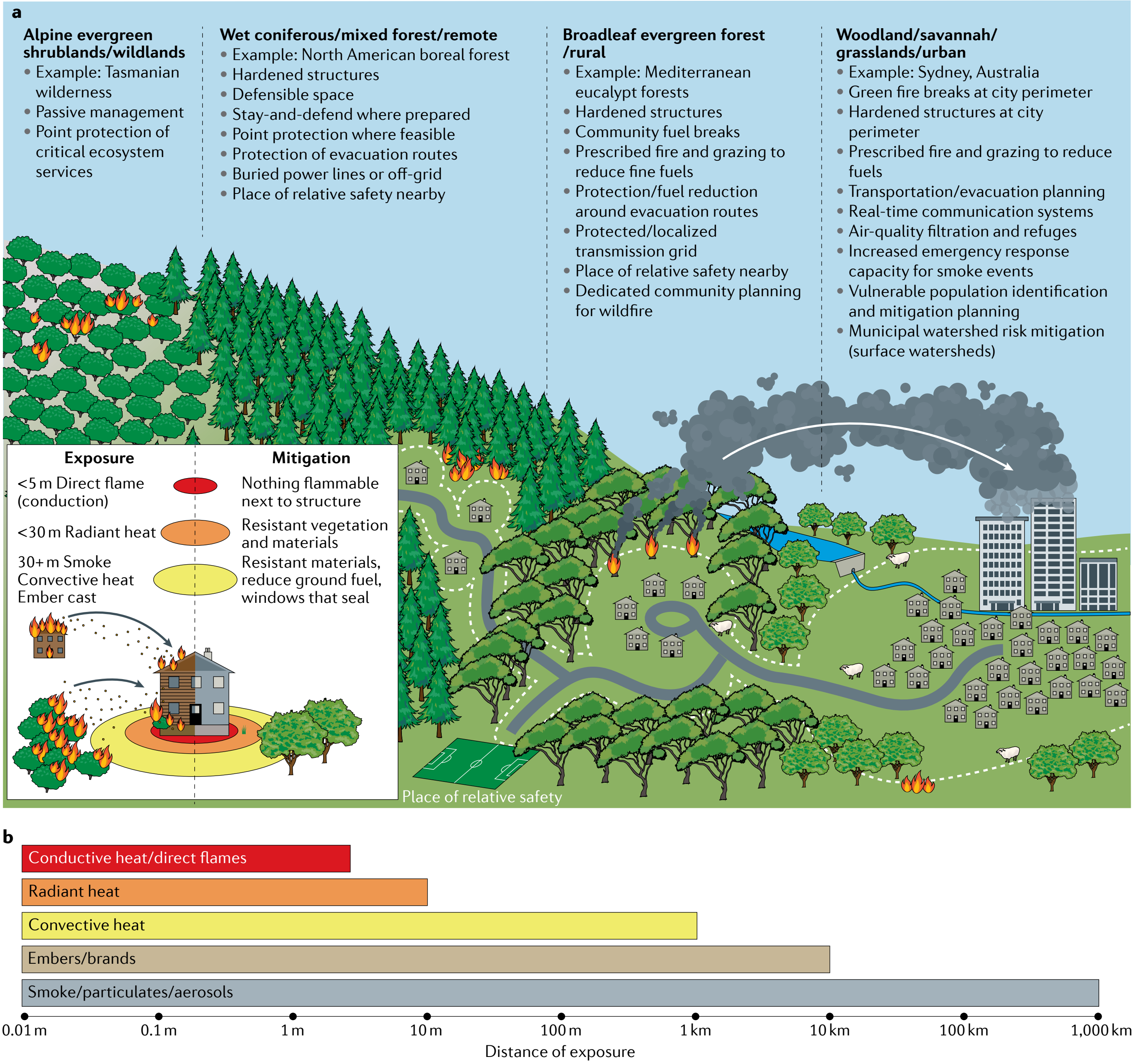

Fig. 6 | **Adaptation to Anthropocene fire regimes on fire-prone landscape. a** | Adaptation and management strategies from densely forested areas to the wildland–urban interface, and at the building scale (inset). The intensity of fire management changes proportionally with human population and economic assets, with strategies ranging from allowing fires to burn in wilderness areas to intensive management on the wildland–urban interface. Each type of management solution will be strongly framed by local conditions and social and cultural factors. **b** | Distance of exposure to conductive heat and direct flames, radiant heat, convective heat, embers and brands, and smoke, particulates and aerosols.

Adaptation and management approaches must be tailored to specific environmental and socio-ecological settings (FIG. 6), which we consider in flammable landscapes and the wildland–urban interface (WUI).

***Flammable landscapes and the WUI.*** It is neither possible nor desirable to exclude fire from fire-adapted landscapes. Rather, sustainable fire management demands careful fuel management to conserve biodiversity, sustain ecosystem services (such as the provision of water and clean air) and reduce the risk of wildfire disasters[142]. Fuel management can involve broad-scale prescribed burning, as it is a cost-effective method to reduce fuel loads and, hence, reduce the risk of uncontrollable fires in frequently burned vegetation, such as savannah and dry *Pinus* and *Eucalyptus* forests[143]. To be effective, however, this approach requires frequent burning because fuels rapidly reaccumulate. Furthermore, large areas must be treated to ensure that enough of the area that is likely to be encountered by a wildfire has been burned[144]. Dense, mesic and naturally infrequently burned vegetation are unsuitable for this fuel treatment unless it

Wildland–urban interface
The intermix of urban areas with flammable vegetation that is the locus of the most deadly and economically destructive wildfires.

**Biomass smoke**
A dynamic mixture of gases and aerosols, made up of organic and inorganic chemical species, emitted during the combustion of biomass.

is combined with mechanical thinning. This latter approach has the potential to increase resilience in US coniferous forests where fire has been excluded for up to a century, with the possible benefit of reduced carbon emissions from subsequent wildfires[145–147].

However, prescribed burning has significant constraints, particularly owing to the potential for shrinking safe weather windows due to climate change[148], and the effectiveness of prescribed burning in altering wildfire behaviour sharply declines under extreme fire weather[149]. Prescribed burning also causes biomass smoke pollution[150]. Smoke from large-scale prescribed burning programmes can cause death and hospitalization, which could potentially exceed the human-health impact of the wildfires that these managed fires are intended to mitigate[151]. Air-quality regulation by governments has demonstrable public and environmental benefits and has driven technological innovation[152], so, in principle, government regulation of the smoke pollution from both wildfire and prescribed fires could drive innovation in fuels management and achievement of more economical, sustainable and safer strategies[153].

Fire management should also draw on indigenous and local knowledge about fire regimes[15,154,155], because these practices have been refined over millennia and have demonstrably sustained biodiversity[16,156]. Yet, it must be recognized that wide-scale 'restoration' of indigenous fire regimes is no longer possible in many environments, as there have been profound socio-ecological changes to indigenous fire practices and environmental conditions have moved outside of the historical range of variability[157,158]. Nevertheless, fire-management approaches that combine traditional ecological and local fire knowledge with mainstream fire-management approaches and technologies must be developed to adapt to changing environmental conditions. Such management is particularly important in the flammable WUI, where the most economically destructive vegetation fires on Earth occur[27].

The WUI is rapidly expanding as a result of growing urban populations[23,141,159,160], particularly in southern Europe, western North America and southern Australia, which have the highest concentration of wildfire fatalities and structural losses[23,141]. There is rapidly increasing firefighting expenditure to protect the WUI — the US fire season in 2018 exceeded USD $3 billion in suppression costs, largely owing to the reliance on fleets of specialized aircraft[159,161,162] (FIG. 3c). Moreover, fires in the wildlands near urban areas can cause extreme air pollution in populated areas. For example, smoke from the 2019–2020 Australian bushfires is thought to have caused 417 deaths (much greater than the 33 recorded direct fatalities) and several thousand hospitalizations for cardiovascular and respiratory problems[163].

The vulnerability of housing on the WUI reflects a constellation of socio-ecological factors that amplifies fire risk, property damage and loss of life[141,164–166]. These factors include the large numbers of ignitions from human sources, ineffective fuel treatments, poor planning, design and regulation of the built environment (particularly the careless intermixing of housing and infrastructure in flammable vegetation) and limited preparation for fire disasters, such as design standards for housing to survive fire, development of evacuation plans and construction of safe places, effective public-education communication, dissemination of advice and emergency warnings. Fundamentally, fire-management challenges in the WUI reflect urban planning and policy failures, which demand reform and the need to enact and enforce national and local laws that control urban development, design and construction[141,165].

More effective protection of urban and WUI areas from wildfires should be achieved by managing fuels through prescribed burning, mowing, grazing and browsing ground-cover vegetation, planting strips of fire-resistant trees to create 'green fire breaks' (REF.[167]) and creating corridors of thinned forest to create 'shaded fuel breaks' (REFS[162,165,168]). China is a world leader in this approach, establishing 364,000 km of green fire breaks to manage landscape fire[169]. Communities and individuals must manage fire risk[65,141,159,162,166] by fire-hardening homes and transforming private property in a partnership model[170], shifting the responsibility from fire-management agencies, which are typically centralized[171,172]. Dissemination of geographically and temporally accurate information on wildfires and smoke hazards though advanced technology, such as geolocation and smartphone apps, can enable individuals to make informed choices about managing wildfire risks[173] and their own exposure to high levels of smoke pollution[174], and planning for prospective evacuations in rapidly changing conditions[175,176]. For instance, the US Environmental Protection Agency has developed a real-time smoke-information smartphone app, Smoke Sense, that combines citizen science and instrumental monitoring of air quality to improve public health[177]. Likewise, the AirRater app in Australia was developed by the University of Tasmania, and includes notifications of the health risk posed by biomass smoke to users[174]. Additional smartphone apps are being developed by Australian, US, Canadian and South African fire-management agencies to disseminate advice and warning of fire danger[176]. A strength of these approaches is that they provide real-time and location-specific information, although they can potentially fail during emergencies if there is a surge of users, communication networks or devices become inoperative and if fires escalate faster than warnings can be updated[178]. Warnings of fire danger and smoke hazards need to be combined with a number of other targeted interventions to protect health and wellbeing, such as provision of fireproof and clean air refuges, and community-level support for medically vulnerable individuals[179] (FIG. 6).

***Preventing fire-related emissions.*** Fire regimes are not only impacted by climate change but could lead to net carbon emissions from terrestrial carbon stores. Tropical savannahs are the most fire-prone biomes on Earth and emit the greatest volume of greenhouse gases annually[50]. Emissions can potentially be reduced through concentrating burning in the early dry season, when fire intensity is lower compared with the late dry season[180]. This approach is being attempted by an Australian programme[181], with claims it has successfully mitigated the emission of non-$CO_2$ greenhouse gases, particularly methane ($CH_4$) and nitrous oxide ($N_2O$). For instance, application of this approach to 28,000 km$^2$ of *Eucalyptus* savannah in Arnhem Land has been estimated to have reduced accountable non-$CO_2$ emissions by 37.7% relative to emissions in the decade prior to the intervention[182]. Careful monitoring and evaluation are required, though, to ensure that managed fire regimes do not have unwanted socio-ecological side effects such as harming biodiversity[183], promoting a grass-fire cycle[184] with declines in above-ground carbon storage due to increased tree mortality[185] or disempowering indigenous communities[186].

Fires associated with tropical deforestation emit carbon stored in vegetation and soil from areas that otherwise rarely burn[45]. To reduce the impacts of deforestation fires on carbon storage in the tropics, deforestation must be reduced through policy, economic incentives and education. Although some progress has been made, these gains can be quickly lost, as evidenced by the 2019 increase in deforestation fires in the Amazon following the abrupt reversal of the Brazilian government's commitments to control deforestation[187] (FIG. 3j).

The increasing occurrence of fires in huge, circumpolar expanses of coniferous boreal forests also needs careful management, as these fires emit greenhouse gases and create smoke that cross international boundaries[188]. These boreal forests and their deep organic soils are one of the largest terrestrial carbon stores, containing somewhere between 367.3 Pg and 1,715.8 Pg of carbon[189]. Around 0.2 Pg of carbon is emitted from the boreal zone annually, and emissions are likely to escalate in response to global warming, and past fire and logging disturbances, stresses that have been shown to strongly interact[51,190]. Reducing boreal forest fire requires a multipronged and international approach, which involves reducing accidental human ignitions through education and enforcement. It will also involve skilful management of natural and anthropogenic fires to create a landscape mosaic of burned and recovering areas, reducing the capacity for extensive fires to develop[123].

Large-scale tree planting and natural-forest restoration has recently been suggested as pivotal to drawing down atmospheric $CO_2$ (REFS[191–193]), but there are substantial caveats to this idea[194–198]. Critically, any large-scale reforestation programme to store carbon must have effective and sustainable fire management, as large expanses of young trees are particularly vulnerable to high-severity fires[199,200]. This vulnerability was exemplified by the widespread destruction of *Pinus* and *Eucalyptus* plantations by fires in Chile, Portugal and Australia during recent fire disasters[96]. Creating fire-resilient timber plantations of flammable but productive timber remains a research challenge, owing to the difficulty and danger of using prescribed burning to reduce fire hazard, and mostly likely will require mechanical removal of fuel[96]. Restoration plantings designed to restore habitat or sequester carbon should focus on either restoring fire-resistant ecosystems[158] or target non-flammable species[167]. Regardless, investment in fire suppression will be mandatory in all cases.

**Pyro-tornadoes**
Extreme fire behaviours can result in intense localized convection that spawns a violently rotating column of burning gases and debris.

## Summary and future perspectives

The flammability of many landscapes is increasing because of the combined effects of changing climate and land-use patterns[3]. The increased risk of economically and ecologically destructive fires can be reduced using planning and urban-design principles, combined with fuel management and fire management. Development of these fire-management interventions requires transdisciplinary research that combines insights from natural and social sciences, engineering and technology, and humanities[33,201,202]. Such research is also prerequisite for improving global and regional fire models of future fire activity[108,121], which are needed to explore the fire–vegetation–atmosphere feedbacks on terrestrial carbon dynamics (FIG. 4). However, achieving better fire management requires addressing a number of key research challenges.

A basic research need is the description of regional fire regimes that quantify the seasonality, frequency, spatial extent and severity of fires, and then the determination of how these patterns are shaped by climate, terrain and vegetation. Identifying the cause of fires, at the most basic level differentiating natural and anthropogenic ignitions, is also essential. Achieving this basic goal demands nationally and internationally coordinated research that can yield insights through comparative analysis of the development of general ecological principles and evidence-based analysis of the effectiveness of fire-management and adaptation approaches. Within the regional scale, research must address how fire behaviour, particularly uncontrollable extreme fire events, is affected by the interactions between climate, weather, terrain, and the load and type of fuel. Indeed, there are increasing reports from frontline firefighters that the behaviour of many wildfires lies well outside their experience and exhibit unusual characteristics, such as pyro-tornadoes, so it is essential that extreme fire phenomena are systematically documented[25].

Better understanding of global and regional trends in fire regimes and vegetation-fire emissions demands improved data acquisition and database assembly. Existing satellite records only allow for coarse-scale mapping, based around a few easily acquired fire-regime metrics, such as seasonality, intensity and area burned[36]. These data, combined with more accurate vegetation mapping, biomass-structure modelling and emissions factors, are essential for accurate estimates of greenhouse emissions and, hence, global carbon budgets[203]. However, the next generation of satellite imagery will enable more complete parameterization of fire regimes[204], including the progression and behaviour of individual fires and fine-grain mapping of fire mosaics[205]. Of prime importance is moving from simplistic counts of fire detection or area-burned mapping to understanding the severity of fires and the associated impacts on vegetation defoliation, plant death, habitat quality and carbon stocks[203]. The recently established Global Fire Atlas will provide a central repository on remote sensing of individual fires and their location, duration, pattern of growth and spatial behaviour[204]. Furthermore, case studies can be undertaken to understand the effects of land and fuel management and firefighting approaches on wildfire behaviour and document extreme fire behaviour[25,206].

Improved understanding and modelling of interactions between fire and the hydrosphere, geosphere, cryosphere and atmosphere is necessary. Fire and fuel cannot be managed without impacts to these other Earth systems, and integrating dynamic feedback processes across systems will be critical to predicting both consequences and beneficial outcomes of future anthropogenic fire regimes. For example, municipal and agricultural water supplies are often dependent on the delivery of water of a consistent quality and quantity from fire-impacted vegetated watersheds[207], so fire management of that vegetation must also consider potential outcomes on projected water storage and delivery[208].

As anthropogenic fire regimes are influenced by human activity, there is a considerable need for data collection to improve quantification and modelling of fire activity and human populations, including their socio-economic status and historical and cultural-political legacies. Anthropological research into 'fire cultures' can improve our understanding of human relationships with fire use and illuminate why some societies have effectively coexisted with flammable landscapes for millennia[15]. Social science is critical in both understanding how contemporary societies relate to fire, smoke and fire-management strategies and identifying policy barriers, in order to establish pathways for transforming landscapes and achieving management objectives. Risk and disaster sciences are similarly important, particularly in exploring linkages between fire and post-fire geophysical disasters, as well as modifying existing established risk frameworks to include fire. Economic models are essential to informing investment in sustainable fire management and understanding the full costs of fire disasters, including human health impacts. A global database (similar in form to the Global Fire Atlas) on the economic costs of wildfire management and economics losses from fire disasters is required[55], as, presently, these data are only available for a few regions (such as the USA and Canada)[54,209], and methods, terminology and data sources are inconsistently applied[26]. Such economic modelling and policy development are also required to design fire-management programmes to reduce, and, ideally, reverse, greenhouse gas emissions from wildfires and tropical deforestation.

Transdisciplinary pyrogeographic research remains difficult to implement because of numerous intellectual and institutional barriers, such as the limited interaction between the humanities and physical sciences[202]. A critical challenge for wildfire adaptation is the capacity to undertake transdisciplinary, applied research that is on the landscape scale and co-designed and funded by affected communities, multiple government and non-government agencies and landowners. Studies of the impacts and effectiveness of firefighting and emergency management responses to major unprecedented fire events, such as the recent California fires and the 2019–2020 Australian bushfire season, are, by definition, difficult to conduct because they cannot be prospectively planned, funded nor approved by regulators. Furthermore, the capacity of the global fire-science community is being increasingly stretched by the surge of anomalous fire events. Ongoing local, regional, national and international investment in training, institutional capacity building and fostering diversity amongst researchers and practitioners and their approaches is urgently required. This needs to be strategically combined with research and development and evaluation of wildfire mitigation and adaptation strategies. Without such investment, wildfire management and adaptation cannot be evidence-based or cost-effective.

Achieving sustainable stewardship of fire regimes requires acknowledging that fire is an inherent feature of the Earth system that has long been modified by humans. Climate change and numerous other anthropogenic effects on fire regimes present a new, urgent challenge for effective human adaptation to vegetation fire. Coordinated transdisciplinary research can lead to the development of fire-management strategies and avoid adverse economic and environmental impacts of fire disasters.

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## Author contributions

D.M.J.S.B. coordinated the project, led the writing and contributed to the design of the graphics. C.A.K. led the design of the graphics and contributed to the writing. J.T.A. led the climate analyses and contributed to the graphic design and writing. F.H.J. contributed to the project development, graphic design and writing. G.R.v.d.W. led the analysis of carbon emissions and contributed to the graphic design and writing. M.F. contributed to the project development, graphic design and writing.

## Competing interest

The authors declare no competing interests.

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