Wildfires under climate change

A burning issue

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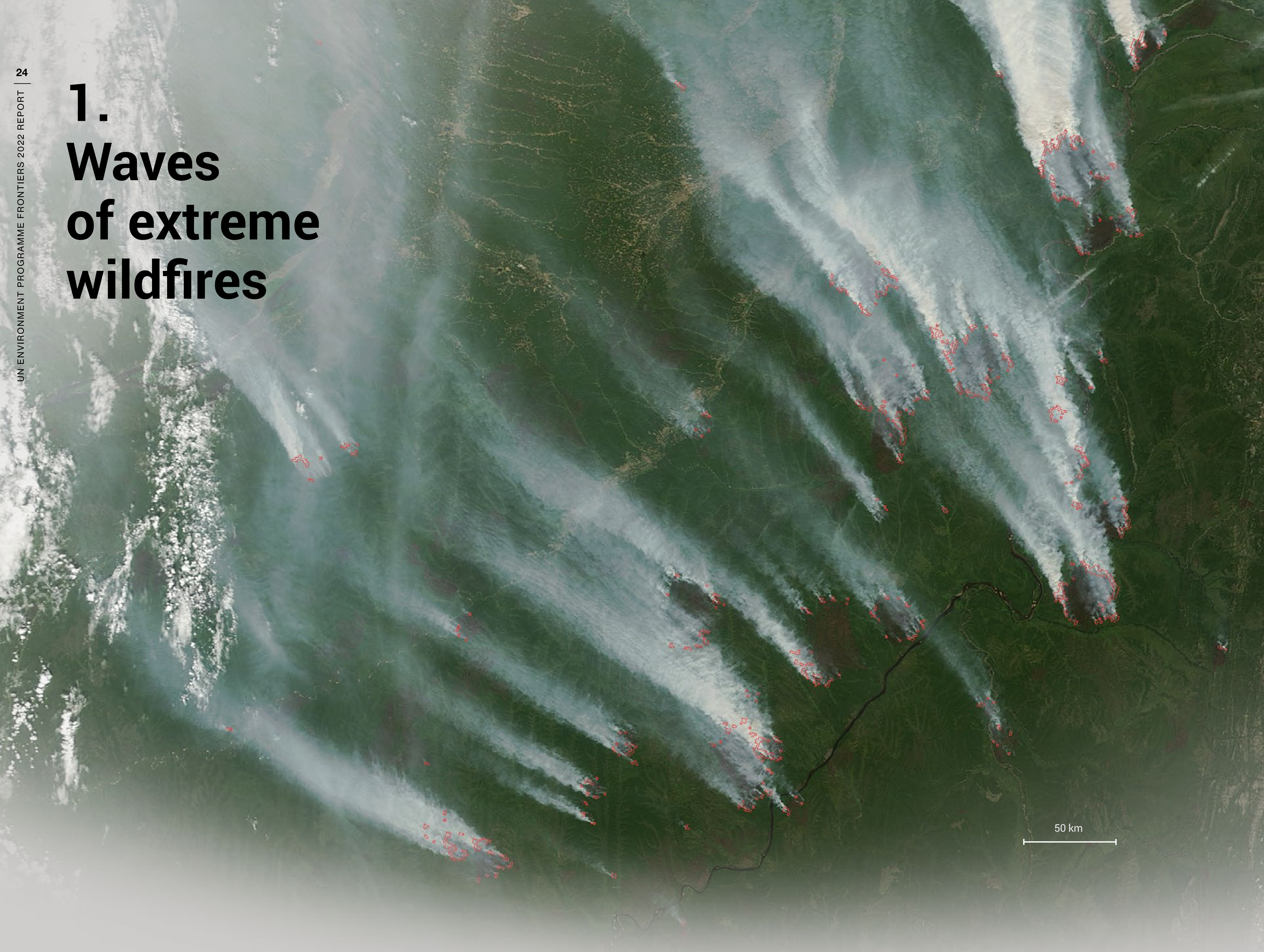
1. Waves of extreme wildfires



On 11 July 2012, more than 25,000 hectares of boreal forests were burning across central and eastern Siberia, Russia. Uncontrolled wildfires were alight from Yugra in the west to Sakhalin in the east. This satellite image shows fires raging near the Aldan River in Yakutia on 10 July 2012.

Source: NASA Earth Observatory

Recent years have seen devastating wildfires in many regions of the world, following heatwaves and droughts. Much news coverage focuses on Northern hemisphere wildfires destroying towns, such as during the extraordinary 2020 fire season in the western United States.[1] The extensive 2021 evacuations from the Greek island of Euboea brought haunting images of what researchers suggest will become more frequent events in Mediterranean countries.[2]

Catastrophic wildfires rage in the global South as well. In 2019/2020, Australia experienced the unprecedented Black Summer fires, with news stories and shocking images broadcast internationally.[3] Despite being a country shaped by fire in many ways, the sheer scale and intensity of the Black Summer fires brought into focus how global warming is adding to wildfire risk.[4-7] The fires burned over 24 million hectares, thousands of homes were destroyed and 33 people lost their lives.[3] The 2019-2020 massive fires destroyed critical habitats for hundreds of species, including those already threatened with extinction.[8]

In Latin America, the rapid and widespread deforestation of savannahs and tropical rainforests, compounded by droughts and the limitations of existing fire management policies, has led to disastrous wildfires in recent decades.[9-11] In 2019, more than 6 million hectares burned in the Chiquitania, Cerrado and Amazon regions in Bolivia, Brazil, Colombia, Paraguay and Peru, mostly within protected areas of native vegetation.[12,13] During the dry season of 2020, another long and destructive wave of wildfires swept through the area.[14,15] Across Africa, fires are visible in satellite imagery throughout the year, adding up to vast burned areas in observation and monitoring records.[15]

Over continents and biomes, there are similarities among these extreme wildfire events in the form of underlying risk factors, hazards and consequences for society and the environment. Long-term effects on physical and mental health are not limited to those fighting wildfires, evacuated, or suffering great loss.[16-20] Smoke and particulate matter from wildfires deliver significant consequences for human health in downwind settlements, sometimes thousands of kilometres from the source.[21-23] Research suggests that the most vulnerable – women, children, elderly, disabled and the poor – suffer the worst ongoing damage from their wildfire exposure, echoing the acknowledged understanding of this same result as the common outcome from most disasters.[24,25]

“The observed trends towards more dangerous weather conditions for wildfires are projected to continue increasing, due to mounting concentrations of atmospheric greenhouse gases, with escalating risk factors.”

The observed trends towards more dangerous fire weather conditions for wildfires are likely to continue increasing, due to mounting concentrations of atmospheric greenhouse gases and attendant escalation of extreme-wildfire risk factors.[4,6,26-34] Beyond changing climate, the heightened intensity of some wildfires can be attributed to land-use change and fire management approaches that do not appreciate the close relationships, evolved over millennia, between vegetation and fire.[11,35-38]

With compounding effects of a heating climate that extends fire seasons and can deliver more natural ignition events, of changes in land use that introduce more combustible fuel and ignition risks, and of more communities built at the wildland-urban interface, significant challenges lie ahead as we learn more about how to live with the fire component of the ecosystems we occupy.

Burned areas in the last two decades

This chart illustrates global burned area patterns from 2000 to March 2021, using the remote sensing data set from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS).

From 2002 to 2016, approximately 423 million hectares of the Earth's land surface burned annually, the majority (67%) on the African continent.[39] A related analysis estimated that from 2003 to 2016 over 13 million individual fires occurred globally, each lasting 4–5 days.[15] On average, each ignition burned an area of 440 hectares globally, while in Australia individual fires burned up to 1,790 hectares.[15]

The data includes all types of burned areas detected – including cropland, pasture, and natural vegetation – regardless of the ignition source, fire types, or reason for burning.

* South Sudan gained independence from Sudan on 9 July 2011. The burned area data prior to the date have been mapped to the present border demarcations of both countries.

See page 38 for complete references.

2. Human influences on wildfires

Wildfires are a natural feature of the Earth system, necessary for the functioning of many ecosystems. Interactions between vegetation and climate over extended periods establish a particular pattern of wildfire recurrence in a defined ecosystem, known as its fire regime.[40] Deviations from the prevailing fire regime – the timing, frequency, size and intensity of wildfires – can drive significant ecological changes in both fire-dependent ecosystems that need fires to thrive and fire-sensitive ecosystems where fires bring more negative than positive effects.[37,41-45]

Humans directly and indirectly alter fire regimes by modifying landscapes and their vegetation, by starting fires as a land management practice where natural fires rarely occur, by suppressing and preventing fires to protect human communities, and by changing the climate.[42] Land clearing, deforestation, agricultural expansion, resource extraction and urban and rural development are all major land-use changes that can interfere with natural fire regimes.[41]

Fire-sensitive tropical rainforests seldom burn naturally, because fire ignitions are rarely sustained in such a humid environment with moist vegetation.[45] Now wildfires have become more common in some regions where they were not expected to occur, including due to climate change as well as other factors such as land-use change and deforestation. In the Amazon rainforest fires are set by humans: native vegetation is cut down, the more valuable timber is selected and removed, and the remains are left to dry until the debris is deliberately set alight to open space for farms and grazing land.[10,11] Forest fragmentation and the eventual breakdown into savannah and grassland create favourable conditions for future wildfires, resulting in the permanent loss of tropical forest ecosystems.[46]

Growing urbanization, as cities expand into wildland, is another important form of land-use change and landscape transformation. Recent decades saw a rapid expansion of cities towards forest areas in many regions.[47] This wildland-urban interface is the area where wildfire risks are most pronounced.[48]

Inappropriate fire management policies, including aggressive fire suppression, and the low recognition of traditional fire management practices and indigenous knowledge, can generate a cascade of challenges.[11,49-51] In some other cases, attempts to eliminate fire from ecosystems, including fire-dependent ones, can lead to build-up of fuel loads and an associated increase in ignition risks.[52-55] Fire management policies such as these can result in fire regime shifts with large and frequent wildfires becoming prevalent.[37,56]

In recent decades, a growing recognition of the need for a system and whole-of-landscape approach that is integrated with the cultural and ecological significance of indigenous land management is helping to promote ecological health and prevent larger, more destructive uncontrolled fires in ecosystems.[57,58] For example, fire management initiatives in Australian savannahs have measured and monitored the effects of prescribed burning that incorporates indigenous wildfire management techniques, with positive results.[57] This approach has provided inspiring examples for other countries, including in Brazil's Cerrado and Botswana's savannah ecosystems.[59]

On 13 June 2020, a vehicle fire ignited vegetation near a highway in Phoenix, Arizona, USA, resulting in a burned area of nearly 26,000 hectares in 3 days.

The satellite image acquired by the Operational Land Imager (OLI) on Landsat 8 shows the burn scar and some active fire fronts as they appeared on 14 June 2020. The combination of natural colour with the infrared signature of active burning enhances detection of ongoing fires through the smoke.

Source: NASA Earth Observatory

Wildfires in the Anthropocene

Fire ecology

What is a wildfire?

A wildfire is a free-burning vegetation fire, including fires that can pose significant risk to social, economic, or environmental values. It may be started maliciously, accidentally, or through natural means.[38]

A wildfire can be short in duration and small in area but more commonly burns for an extended period of time and over a wide area. The behaviour of a wildfire can be largely benign around its perimeter but will sometimes be characterized by periods of rapid spread and intense behaviour at its front, against which suppression and other risk mitigation efforts may be ineffective. The impacts of a wildfire may be immediately and directly apparent or may materialize some time after the fire is extinguished.[38]

While wildfires can occur naturally, most are a result of human actions such as clearing land after industrial deforestation and for agriculture or human settlement, managing pastures for grazing livestock, and negligence.[38]

Depending on the interactions between vegetation and climate, wildfires generally behave according to a pattern specific to the surrounding ecosystem, known as the *fire regime*. The attributes of a fire regime include frequency, burn extent, intensity, severity and seasonality.

Wildfires can occur naturally when three elements combine:

Ignition
heat from the sun or lightning strike to ignite a fire

+ **Fuel**
sufficient combustible materials to feed the flames

+ **Weather**
conditions such as temperature, wind, or relative humidity to enable spread

Wildfire and ecosystems

Wildfires play a key role in maintaining ecological functions and biodiversity. Many ecosystems evolved to incorporate wildfire recurrence and depend on them to maintain ecosystem health. For instance, some plants need recurring fires to trigger germination and burn off competing vegetation. Because species in a given habitat have adapted to a specific fire regime, any change can impact both species and ecosystem as a whole.

Types of wildfires

Depending on biomass fuel and weather conditions, there are three types of wildfire. A single fire event may exhibit all or a combination of these three fire types.

Crown fires
These ascend from ground to tree crown and can spread through the forest canopy. Common in Mediterranean-climate woodlands and boreal forests. The most intense and dangerous wildfires, often the most difficult to suppress. Spread generally requires heavy fuel loads and strong winds.

Surface fires
These burn through leaf litter, dead material and vegetation on the ground. Predominant and frequent in grasslands and savannahs where productivity is high. Also common in woodlands and forests where litter is the main fuel. Surface fires can spread vertically by igniting bushes and shrubs to become crown fires.

Ground fires
These burn decomposed organic subsurface layers of soil and usually do not produce visible flames. Difficult to fully suppress, ground fires can smoulder over winter and may re-emerge in spring. Most common in peatlands and bogs, and can develop into surface fires.

Fire-dependent plants

In fire-prone ecosystems, many plant species depend on recurring fires in their life cycle. Fires trigger flowering, seed dispersal, or seed germination.[36]

Some species common to boreal forests and Mediterranean-climate regions store seeds in cones for years until a fire event triggers their release.

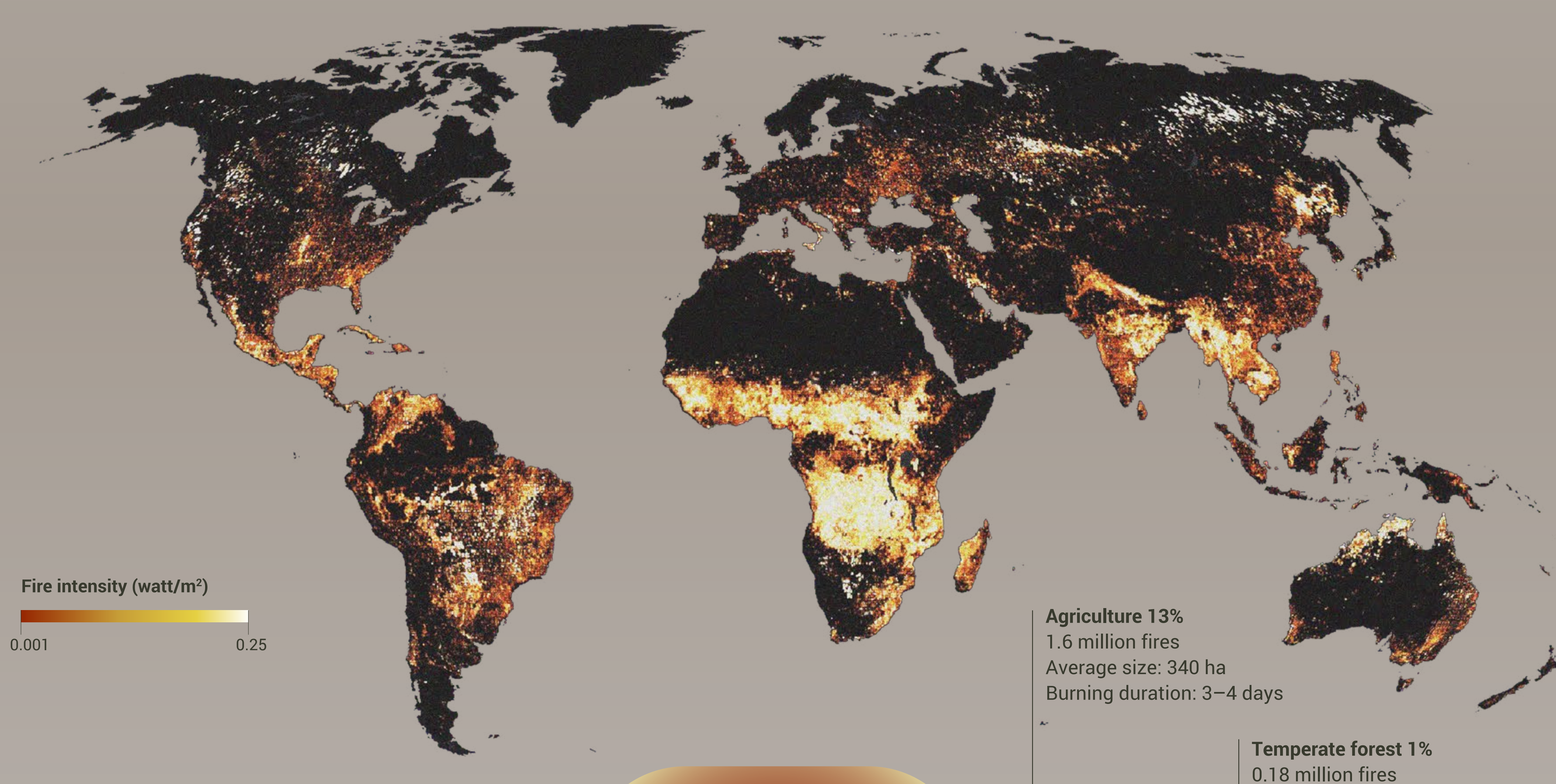
Wildfire events stimulate flowering in bulb-producing plants such as orchids and lilies, and in perennial grasses.

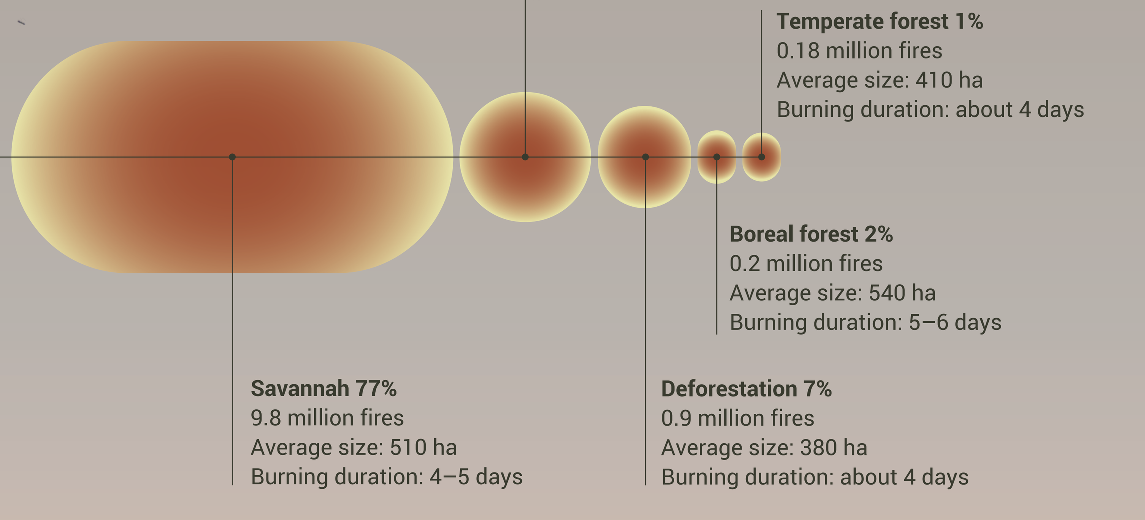
Smoke and charred wood can also induce seed germination in many species in fire-prone shrublands.

Where fires burn

The map shows active fires of all types observed from 1 January to 20 September 2021. The image was created by merging still frames extracted from NASA's time-lapse video of active fires. For best viewing of the dynamic changes in fire intensities over time, go to NASA Scientific Visualization Studio.

See the timelapse ▸





Number of fires detected from 2003–2016

From 2003 to 2016, over 13 million individual fires occurred globally with mean durations lasting from 4 to 5 days, varying by continent and fire circumstance.[15] Average burned area of each fire was 440 hectares.[15]

Fire regimes are changing

Changing fire regimes in selected biomes

The table adapted from Bowman *et al.* (2011)[35] summarizes how regimes in selected biomes from low to high latitudes have changed following global industrialization.

Biome	Tropical rainforest	Tropical savannah	Mid-latitude desert	Mid-latitude North American seasonally dry forests	Boreal forest
Pre-industrial fire regime	Very infrequent low-intensity surface fires with negligible long-term effects on biodiversity	Frequent fires in dry season causing spatial heterogeneity in tree density	Infrequent fires following wet periods that enable fuel build-up	Frequent low-intensity surface fires limiting recruitment of trees	Infrequent high-intensity crown fires causing replacement of entire forest stands
Post-industrial fire regime	Frequent surface fires associated with forest clearance causing a switch to flammable grassland or agricultural fields	Reduced fire due to heavy grazing causing increased woody species recruitment	Frequent fires due to the introduction of alien flammable grasses	Fire suppression causing high densities of juveniles and infrequent high-intensity crown fires	Increased high-intensity wildfires associated with global warming causing loss of soil carbon and switch to treeless vegetation

Source: Adapted from Bowman *et al.* (2011)[35]. Published with permission from John Wiley & Sons Ltd.

Photo credit for mid-latitude North American seasonally dry forest: kenkistler / Shutterstock.com

Land-use change

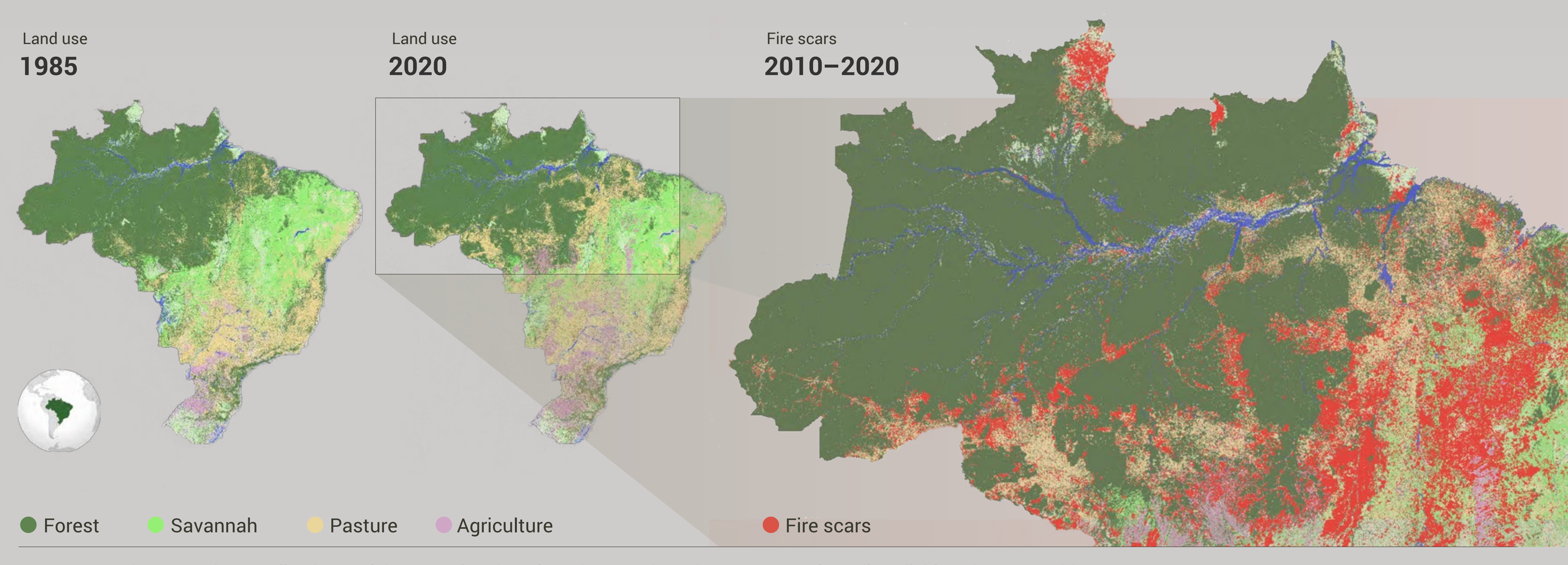
Land-use changes associated with agriculture, deforestation and urban development are driving substantial changes to fire patterns in a wide range of ecosystems.[35]

People frequently use fires to manage land where wildfires are rare, or suppress fires where wildfires are common. Land conversion from native vegetation changes fuel properties that may lead to higher severity or frequency of wildfires.

Around the Mediterranean, reduction in pastoral activities has converted grasslands into highly flammable shrublands.[36]

In tropical rainforests where most species have not evolved to recover rapidly from fire, wildfire is often used to convert forests to ranches and farmlands. This land clearing changes fire regimes at local scale, which becomes ecosystem conversion at larger scale.[41]

In Brazil, land-use changes such as deforestation and agriculture have resulted in an increase in fires across the country, including in the Amazon rainforest region where fires were previously rare.



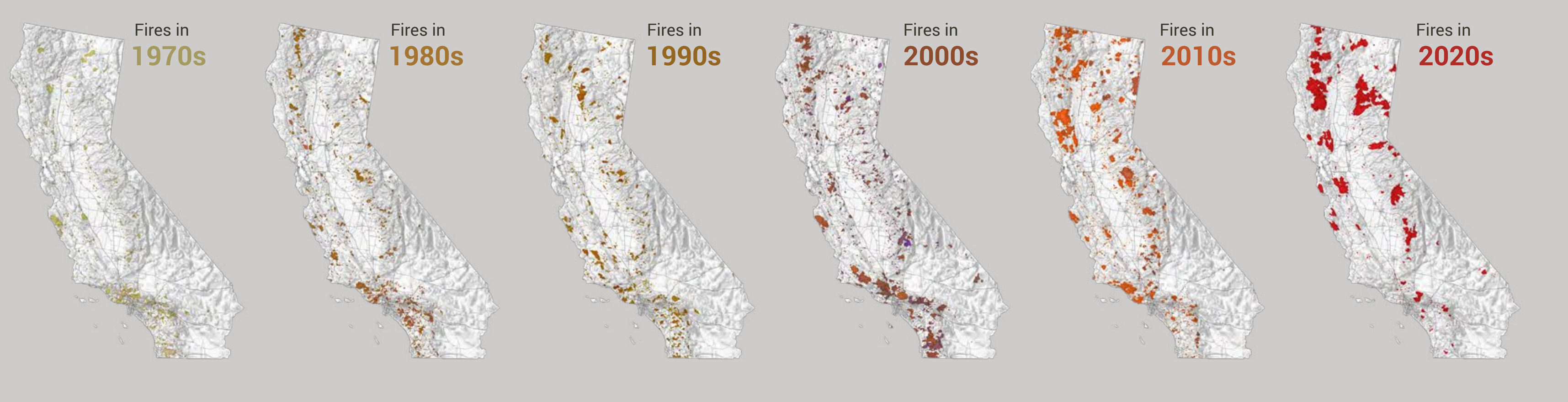
Source: MapBiomas Project - Collection 6 of the Annual Series of Land Use and Land Cover Maps of Brazil available at http://mapbiomas.org.
MapBiomas Project is a multi-institutional initiative to generate annual land use and land cover maps from automatic classification processes applied to satellite imagery.

Expanding wildland-urban interface

Urban development at the wildland-urban interface requires that fire risks be managed and aggressively suppressed, resulting in changes to natural fire regimes.[42]

Land development not only modifies vegetation, but the fire suppression and exclusion policies, intended to protect human lives and properties, also lead to fuel accumulation and severe fires when they do burn.[35,37]

The burned area and average size of wildfires in California, USA, have increased in the last decades. Rapid urbanization along the forest edges, accumulation of biomass fuels from decades of fire suppression and extreme drought and heat exacerbated by climate change contribute to the surge in large fires.



Source: NASA Earth Observatory (https://earthobservatory.nasa.gov/images/148908/whats-behind-californias-surge-of-large-fires)

Fire and invasive species

Human activity is largely responsible for introducing invasive species that can alter fire regimes by changing the vegetation structure within the ecosystem, changing fuel quantity and properties.[37]

Altered fire regimes can create conditions unsuitable for native vegetation to recover after a wildfire, but suitable for invading fire-tolerant species to flourish.

Across many ecoregions of the USA, invasion by certain non-native grasses has increased fire occurrence by 230% and fire frequency by 150%.[44]

Many invasive grasses have high fuel biomass and low moisture, creating conditions favourable for wildfires. Some of the most successful invasive grasses germinate seeds when cued by heat and smoke.

3. Changing climate, changing fire weather

In November 2019, numerous bushfires were burning north of Sydney, Australia, with thick smoke blowing towards the coastal cities of Coffs Harbour and Port Macquarie. Air quality in the affected cities reached hazardous levels. Record-breaking temperatures, strong winds and a persistent lack of rainfall enabled massive bushfires across the state of New South Wales.

Source: NASA Earth Observatory.

Globally, many types of extreme weather events are now more intense and occurring more frequently than in the past due to anthropogenic climate change.[27,28] Long-term warming trends show that most years are now hotter than those observed before 1950 in 41 out of the world's 45 regions.[28] Hotter temperatures, coupled with more droughts, lead to longer fire seasons and more likelihood of dangerous fire weather conditions.[1,26-34,60,66]

Research focusing on western North America shows that heatwaves and multi-year droughts are not only fostering more wildfires, but the wildfires are increasing in severity and burning larger areas.[30,34,61] In South America, severe and prolonged droughts and higher air temperatures are associated with increased fire incidence and severity in humid tropical areas and seasonally flooded wetlands, including areas where wildfires were unprecedented.[14,62-65] In the temperate climate region of Australia, rainfall in the period leading to the fire season has declined by over 10 per cent since the late 1990s.[67] Based on over 100 years of data, 2019 was Australia's hottest and driest year on record.[5,66,67] In Chile, New Zealand and parts of Africa, research has also shown the influence of climate change in increased drought conditions and forest fire activity.[62,68-71] In Southern Europe and around the Mediterranean Sea, climate change is likewise driving more dangerous fire weather conditions as the entire Basin transitions into a more arid system.[2,28,35,72,73]

> "Globally, many types of extreme weather events are now more intense and occurring more frequently than in the past due to anthropogenic climate change. Hotter temperatures, coupled with more droughts, lead to longer fire seasons and more likelihood of dangerous fire weather conditions."

Lightning is an important natural ignition source for wildfires and frequency of lightning strikes in some parts of the world are projected to increase with a changing climate.[74-81] In recent years climate-driven lightning ignitions account for the majority of burned areas in the North American boreal forests.[82] An increased frequency of dry lightning – a type of lightning that occurs with little or no precipitation – has also been documented in some parts of southeast Australia in recent decades, while some areas experienced a decline.[83] Of the total area burned by wildfires, a significant proportion can be attributed to lightning ignitions, because they can occur variably over time and space and they spread in remote regions that are difficult to reach with response capabilities.[74]

Another phenomenon that has become more frequently reported in Australia and North America in recent decades is the fire-generated thunderstorm.[4,6,84-89] A characteristic of more extreme fire events, these thunderstorms form in wildfire smoke plumes, generating what are known as pyrocumulonimbus clouds. The frequency of weather conditions associated with the occurrence of fire-generated thunderstorms is increasing over time in parts of southern Australia, with these increases projected to continue.[4,77,86,90] Fire-generated thunderstorms can contribute to more dangerous conditions for fires on the ground, including more erratic wind speeds and changes in direction, as well as generating lightning that can ignite new fires far beyond the fire front.[85] They illustrate the risk of dangerous feedback loops between the fire and atmospheric processes.

Available biomass fuel is a key factor driving fire intensity under the uncertain influence of climate change. Fuel loads may increase due to the CO_2 fertilization effect when higher carbon dioxide concentrations at ground level encourage certain plant types to thrive.[91-93] While the bulk of organic material could increase, lower relative humidity would turn the greater bulk into dry fuels for wildfires. Fuel load has also increased due to the practice of wildfire exclusion in some cases.[26,94] Better comprehension of fire-dependent ecosystems, and fire ecology as a whole, is fostering the shift toward integrated fire management including the use of controlled and prescribed burning at appropriate times and under the correct conditions to reduce fuel loads.[42,95]

While climate change is already influencing wildfires, wildland fires may likewise be influencing climate change.[28,96,97] Loss of the Amazon rainforest and thawing of Arctic permafrost are considered two possible tipping elements that could potentially accelerate climate change.[28,98,99] Recent research has indicated deforestation in the Amazon is shifting the region from a carbon sink to a carbon source and permafrost thaw is accelerating in the Siberian Arctic, with fires as contributing factors in both cases.[87,88,100]

Climate change:
Fire weather is becoming more extreme

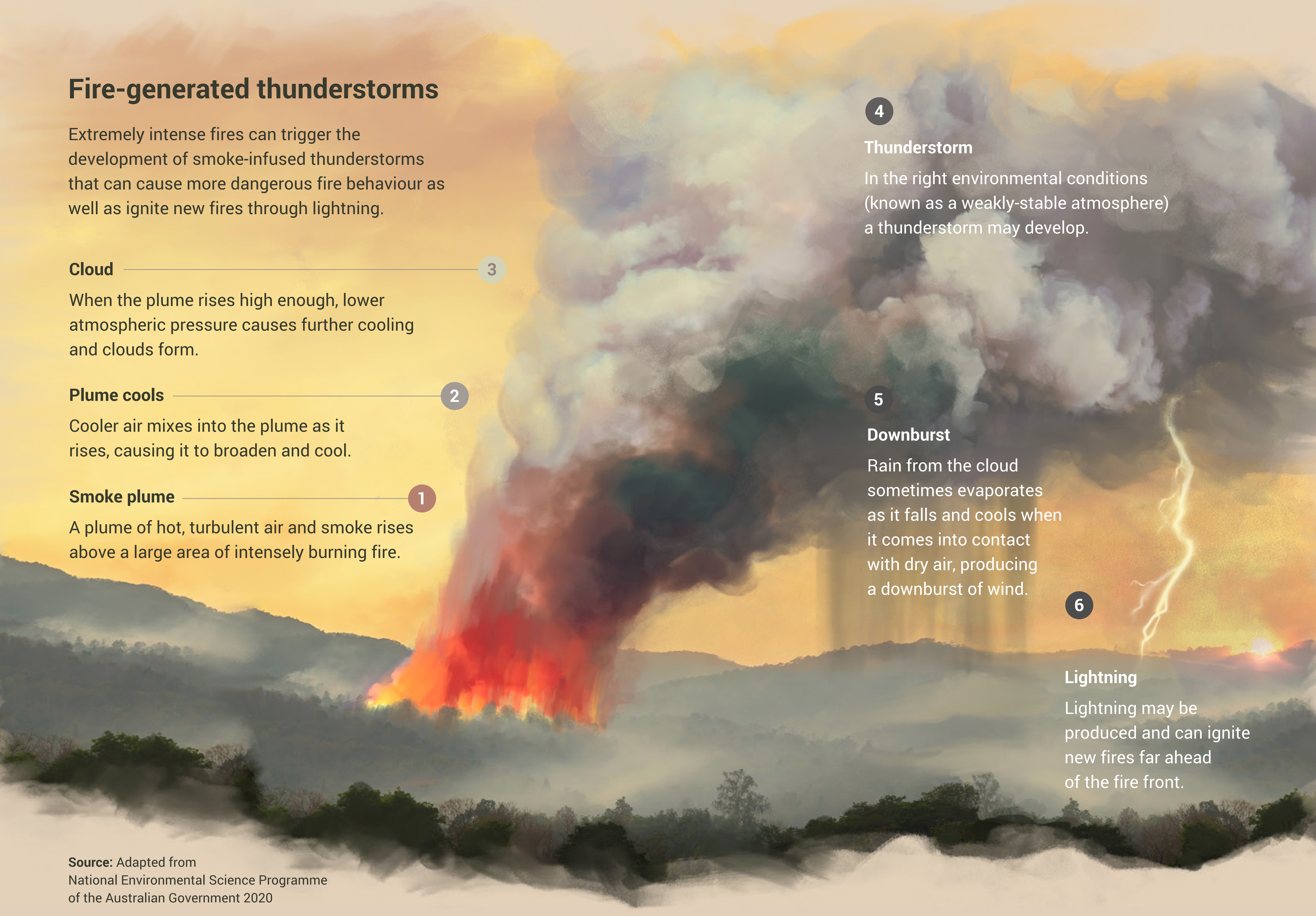
Climate change is increasing the risk of large and more intense fires.[5,6,42] Climate directly affects the production and condition of biomass, and weather that supports fire ignition and propagation. In the months preceding fire season, prolonged warm and dry weather reduces vegetation moisture, increasing risks of fire ignitions that may develop into wildfires and spread. In contrast, unusually high rainfall increases plant growth that then may serve as fuel in the next dry season. Large fires in woody ecosystems occur during prolonged drought events, such as in regions affected by El Niño variability.[5,36]

Lightning ignition

Lightning is an important natural ignition source for wildfires. Lightning strikes are projected to increase in frequency in some parts of the world as climate changes. Lightning ignition is the predominant driver of massive wildfires in the boreal forests of North America and northern Siberia.[60]

Fire-generated thunderstorms

Extremely intense fires can trigger the development of smoke-infused thunderstorms that can cause more dangerous fire behaviour as well as ignite new fires through lightning.



Cloud (3)
When the plume rises high enough, lower atmospheric pressure causes further cooling and clouds form.

Plume cools (2)
Cooler air mixes into the plume as it rises, causing it to broaden and cool.

Smoke plume (1)
A plume of hot, turbulent air and smoke rises above a large area of intensely burning fire.

(4) **Thunderstorm**
In the right environmental conditions (known as a weakly-stable atmosphere) a thunderstorm may develop.

(5) **Downburst**
Rain from the cloud sometimes evaporates as it falls and cools when it comes into contact with dry air, producing a downburst of wind.

(6) **Lightning**
Lightning may be produced and can ignite new fires far ahead of the fire front.

Source: Adapted from National Environmental Science Programme of the Australian Government 2020

Impacts of extreme wildfires on the Earth's system

Atmospheric pollution
Large wildfires emit vast amounts of atmospheric pollutants, such as black carbon, particulate matter, and greenhouse gases. These pollutants may be transported a long distance and deposited over remote landscapes, including glaciers.

Changed albedo
Atmospheric transport and deposition of soot reduces surface albedo and enhances snow and ice melt. Soot deposits from Amazon basin wildfires are found to increase the melting of the Andean glaciers.

Carbon sink turns into carbon source
Large and frequent wildfires in boreal and tropical forests may transform terrestrial carbon storage into major sources of greenhouse gases.

Water pollution
Following severe wildfires, elevated sediment levels in rivers increase turbidity, alter water temperatures, and affect fish abundance.

Post-wildfire erosion brings a range of nutrients and contaminants into water bodies, affecting water quality and aquatic species.

Nutrients such as nitrogen and phosphorous released into water bodies can cause eutrophication and reduce the levels of dissolved oxygen, posing a risk to aquatic organisms.

See page 40 for a complete reference.

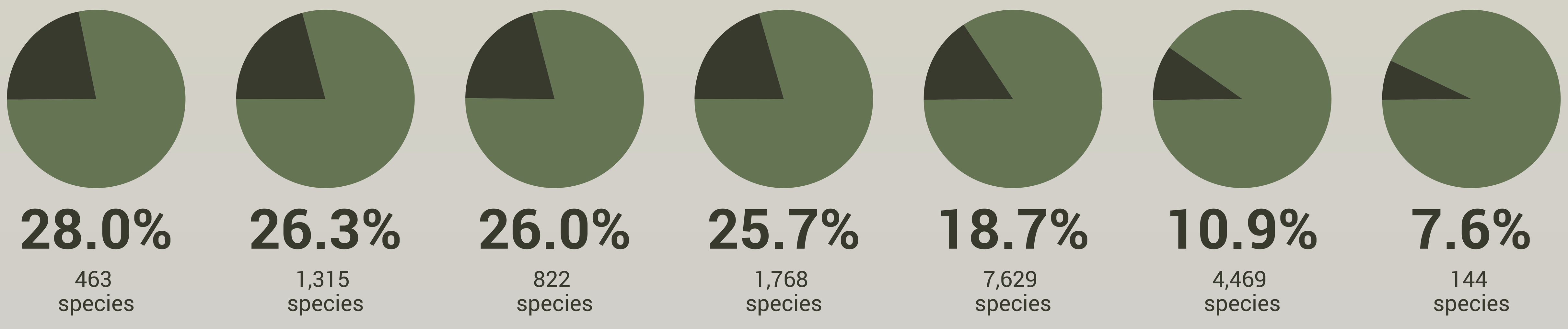
Erosion
Wildfires increase the susceptibility of soil to erosion when exposed to postfire precipitation. Erosion normally occurs before vegetation has redeveloped. Slope failures can lead to catastrophic debris flows and landslides in some environments.

Ocean fertilization
Large, intense wildfires release enormous amounts of aerosols, including bio-essential trace metals such as iron. Atmospheric transport of iron-rich aerosols from the 2019/2020 Australian extreme wildfires caused large-scale algal blooms in the South Pacific over a 4-month period.

Biodiversity loss
More frequent and more intense wildfires can produce a long-term change in plant species composition and structure of forest ecosystems. Reburns may also become more common, potentially reducing post-fire regeneration. Depending on the original forest type, reburns could possibly result in a shift to non-forest vegetation.

Species under threat of altered fire regimes

Percentage of species threatened by altered fire regimes including fire exclusion per habitat



Source: Kelly *et al.* (2020). See page 40 for a complete reference.

4. Wildfire management improvements in the face of further climate changes

As the loss and damages from extreme wildfires mount, needs for both prevention and response management approaches are gaining attention. The threats will only increase as anthropogenic climate change intensifies, including in cases where land-use changes fail to follow best practices to conserve ecosystem resilience and landscape integrity.

While developed country practices have often emphasized fire exclusion, many developing countries lack capacity to manage fires, beyond responding once the disaster becomes an immediate threat to life and property. Effective fire management is important in fire-dependent ecosystems, such as savannahs and grasslands, where fuel loads build up and increase fire risks, especially in the peak of the dry season.[53] Whether ignited by lightning or humans, fuel loads that have accumulated over years or decades can result in uncontrollable wildfires. In contrast to total fire exclusion approaches, recognition of indigenous practices that maintain manageable fuel loads and productive ecosystems through periodic controlled burns is now a common practice in some regions.[50,57,59,107,110] However, certain countries still follow wildfire suppression policies, where attempts to exclude fire completely from the landscape can add to the intensity and severity of dry season wildfires.[55]

Community-owned solutions in Latin America

Divinópolis, Minas Gerais, Brazil **Credit:** Christyam de Lima / Shutterstock.com

The absence of adequate fire management policies in Latin America dates back some centuries.[55,101,102] Yet increasing extreme wildfire events have demanded special attention from rural, traditional and indigenous communities, who are not only directly affected by such disturbances, but are also restrained in managing their own territories in some cases.[10] These peoples have therefore implemented ancient fire management practices that deliver the safest outcomes by protecting themselves, conserving the natural ecosystems essential to their livelihoods, producing crops, and preventing wildfires spreading.[10,50,103]

In the last decade some Latin American governments have recognized traditional fire knowledge and learn from these ancient fire management techniques to adjust their wildfire prevention strategies.[55,103] In 2014, a pilot programme of integrated fire management was initiated in Brazil, encouraged by the Brazilian-German Cooperation Project "Prevention, Control and Monitoring of Bushfires in the Cerrado", and inspired by a successful Australian abatement and carbon sequestration accounting methodology.[104,105]

The programme started in 3 Cerrado protected areas and after 5 years scaled up to 74 areas distributed across all Brazilian biomes.

This integrated fire management reduced the area burned by late dry season wildfires by up to 57% and mitigated 36% of the associated greenhouse gas emissions.[50,106] In addition, more than 2,000 local, traditional and indigenous fire brigade members are being hired and trained annually to operate in preventive and suppression activities, as well as to collect data for assessing the effects of different fire regimes on plant and animal species.[107,108] A concerted effort to hire and train indigenous women from the Xerente community includes focus on equipment, mobilization and controlled fire techniques, safety, as well as general environmental education.[108]

The programme's reach is still limited to some protected areas, and most of the Brazilian territory is still highly vulnerable to catastrophic wildfires, such as those experienced in 2019 and 2020. Nevertheless, there is great potential for rural landowners and the government to scale up these successful management practices to reduce repeated annual wildfire losses and risks.

Longer fire seasons as influenced by climate warming can hamper the practice of controlled burns since the conditions for safely undertaking these fuel reduction burns are specific. Rising temperatures and increasing fuel availability, through longer growing seasons and hotter, drier weather, may change opportunities for safe controlled burns, which has consequences for the long-term management of wildfire risk.[91]

Long-range planning depends upon various cooperative components among countries and world regions, including the sharing of resources such as aircraft and firefighters between the Northern and Southern Hemispheres. This worked well when fire seasons did not overlap. Now, with longer fire seasons and more intense demand on firefighting resources during extreme wildfires, this sharing of capabilities will become increasingly difficult.[3,34]

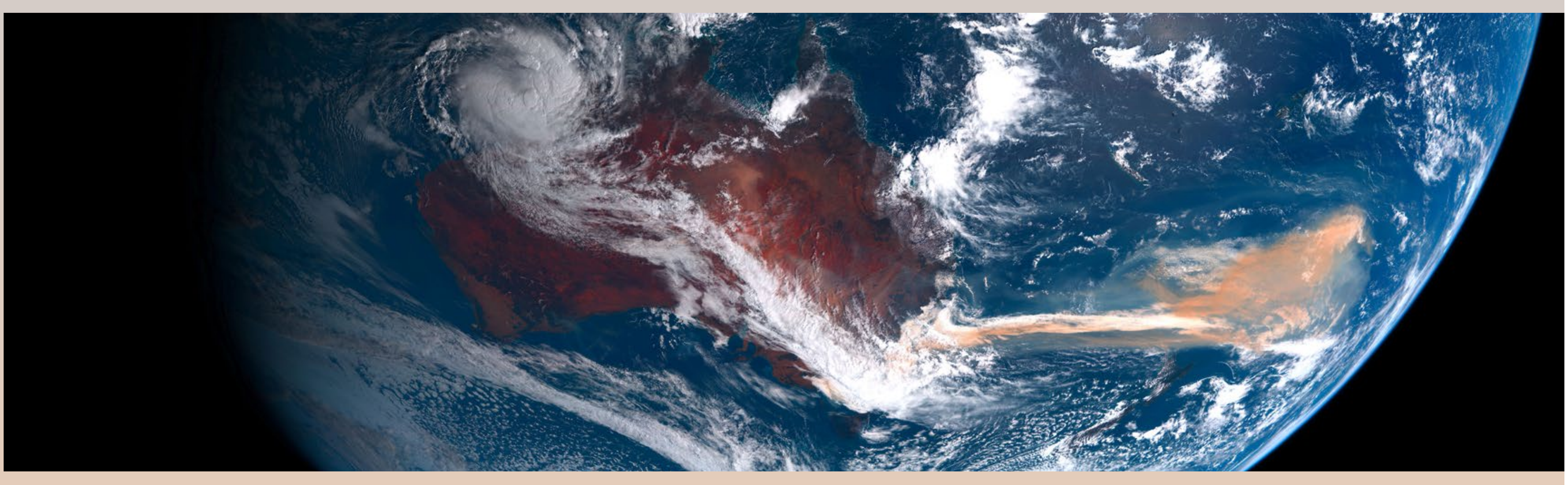
The Royal Commission investigating Australia's 2019/2020 fires presented a wide-ranging set of recommendations, comprehensively covering improved planning, policies, and practices; increased fire-fighting capabilities; enhancing community resilience; and land management strategies that include indigenous practices of controlled burning.[3] The recommendations supported improved design standards for buildings and infrastructure at the wildland-urban interface. This could provide a practical means to incorporate climate change science into routine practices for enhanced resilience, using knowledge of how risk factors have already changed and are likely to continue changing.

The next decade will be critical in building greater resilience and adaptive capacity to wildfires. Use of participatory approaches and involvement of vulnerable groups in all phases of preparedness and response is necessary.[109] Implications for children, women, elderly, people with disabilities, and other at-risk groups can affect whole communities and society at large, both at the time of the extreme event and for years afterwards. Local knowledge can help address questions of ecological integrity and social justice.[110] Calls for further research should address vulnerable groups' exposure to hazard risks before, during and after extreme wildfires.

Additional and improved research on reducing fire risk should include cost assessments integrated with social science and environmental assessments of how effective different actions might be.[110] Enhanced scientific understanding of extreme wildfires should examine how land-use change or land management affects these events. Further research should explore how lightning and vegetation conditions may change in the future, noting considerable uncertainty due to the limitations of currently available climate modelling methods, especially through observations and data collection on extremes including wildfire-generated thunderstorm systems.[84]

Pressure will become more pronounced with further loss and damage that climate changes bring. To avoid the disastrous impacts of worsening extreme wildfires, our ability as communities to prepare for, respond to and manage these extreme fire events must match or exceed the rate of climate change influence accelerating their threat.

Building resilience: new tools and approaches to wildfire management



The image taken on 6 January 2020 shows the long-range atmospheric transport of aerosols from the unprecedented wildfires along the south-eastern coast of Australia towards the broad South Pacific. The oceanic deposition of wildfire aerosols stimulated large-scale phytoplankton blooms. **Source:** Japan Meteorological Agency and NASA

The increased frequency and intensity of natural disasters are posing a greater challenge to existing approaches to disaster risk reduction. New tools offer an enhanced ability to address systemic disaster risk. Globally, refinements in modelling and observations data, including from remote sensing capabilities – satellites, ground-based radar, lightning detection, and data processing – facilitate improved systems for monitoring, predicting and managing wildfires.

The monitoring and data handling power offered by systems such as the European Union's Copernicus programme on Earth observations and the US National Aeronautics and Space Administration are supporting efforts worldwide.[112] The Latin-American Regional Network for Remote Sensing and Forest Fires enables joint efforts and resolutions for fire management operations in Latin America.[113] Brazil's National Institute for Space Research promotes research and enhances monitoring capacity throughout the region with the Queimadas Programme, developing innovative tools for wildfire risk detection and frequently updated heat source information.[114]

South Africa uses a nested model for fire prevention and management, through the Working on Fire programme, in which provincial fire protection associations coordinate with district and local counterparts to develop community skills and employment focused on fire management and firefighting.[115]

Australia now has long-range prediction capability for fire weather conditions, providing guidance to fire agencies to help with decision-making over a broad range of timescales. Climate change projections are also provided to emergency management groups, including fire agencies and planners. This aids evidence-based decision-making on climate hazards related to environmental management, energy, infrastructure, health and finance sectors.[116]

The *Australian National Disaster Risk Reduction Framework*, endorsed into national policy in March 2020, identifies climate change as a fundamental driver for building disaster resilience and taking a systems approach to managing the complexity inherent in disaster reduction and response.[117] It recognizes the importance of developing resilient communities through social and economic networks that cooperate and share responsibility in responding to disasters and adapting to climate change.[118,119] In recent years, the country's approach to disaster management has included an emphasis on strengthening resilience and capacity before disaster strikes.[117] Establishing a network and national capability of knowledge and skills through partnerships, education and professional programmes across sectors is fundamental not only for wildfire management, but also for broader resilience to natural disasters.[120]

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