2 Understanding wildfire risk in a changing climate

This chapter provides an overview of the state-of-the-art scientific knowledge on wildfires, shedding light on the key factors that influence wildfires and their characteristics, as well as on how wildfire trends are changing globally. It discusses how anthropogenic climate change and human activity influence such changes, exacerbating the conditions for the occurrence of extreme wildfires. The chapter provides a comprehensive assessment of the environmental and socio-economic impacts caused by wildfires.

2.1. A critical moment to address wildfire risk

Extreme wildfire risk is growing, as demonstrated by the unprecedented frequency and severity of wildfires that have occurred in recent years in many regions of the world. Wildfires threaten communities and ecosystems and cause significant economic disruption. In the summer of 2019-20, the hottest and driest summer on record in Australia, an extreme wildfire season burned between 24 million and 40 million hectares of land (Royal Commission, 2020[1]). Altogether, the 2019-20 wildfires killed an estimated 3 billion animals and caused USD 23 billion in economic damages (EM-DAT, 2023[2]; WWF-Australia, 2020[3]). Between 1980 and 2021, the United States experienced 20 wildfires that caused economic damages of over USD 1 billion, and 80% of them occurred after 2000 (NCEI, 2023[4]; US EPA, 2022[5]). In particular, the 2018 Camp Fire in California, United States, killed 88 people and caused USD 19 billion in direct economic costs (EM-DAT, 2023[2]). In addition, the seven largest wildfires ever recorded in California all occurred after 2017 (Cal Fire, n.d.[6]). The duration of the fire weather season, which marks the annual period in which meteorological conditions are conducive to fire, is also on the rise in most areas of the world. On average, the duration of the wildfire season rose by 27% globally between 1979 and 2019 (Jones et al., 2022[7]).

Climate change has been identified as one of the key drivers behind these extremes. By affecting temperature, precipitation and wind patterns, as well as the likelihood of extreme weather events, climate change influences wildfire occurrence, spread and intensity by altering fire weather conditions, the amount and conditions of vegetation available to burn, as well as the likelihood of ignition (Ellis et al., 2021[8]; IPCC, 2022[9]; Romps et al., 2014[10]; Halofsky, Peterson and Harvey, 2020[11]; Stephens et al., 2018[12]; UNEP, 2022[13]). For example, climate change is estimated to have doubled the total forest area burned in the western United States between 1984 and 2015 (Overpeck, Dean and Stapp, 2018[14]). The extreme fire weather that facilitated the Australia wildfires in 2019-20 was estimated to be at least 30% more likely because of climate change, while the extent of the 2017 extreme wildfires in Canada was 7 to 11 times higher because of climate change (van Oldenborgh et al., 2021[15]; Kirchmeier-Young et al., 2019[16]).

Extreme wildfire activity is projected to increase further in most regions of the world due to climate change. Under a high-warming scenario, many parts of the world are expected to experience longer wildfire seasons, extending up to 40 days per year in many parts of the world (Xu et al., 2020[17]). The burned area in Greece is projected to grow up to 20% by 2100 (compared to 2010 levels) under a high-emission scenario, which is associated with an annual direct firefighting cost of EUR 40 million to EUR 80 million by 2100 (Bank of Greece, 2011[18]). In Portugal, wildfire-induced losses in the tourism sector are projected to reach EUR 62 million annually by 2030, increasing fourfold by 2050 (Otrachshenko and Nunes, 2022[19]).

This chapter first provides an overview of the concept of wildfires and a discussion of the ecosystems in which wildfires are a natural part of the landscape and those in which they are not. It then reviews the changing patterns in wildfire frequency and severity, shedding light on how climate change and other human-induced factors are driving these trends in observed and projected wildfire risk. This is followed by a discussion of the impacts wildfires have on the climate system, as well as on ecosystems, human health and the economy. The chapter concludes by highlighting how these changes in wildfire occurrence are reflected in government spending.

This chapter aims to distil policy-relevant insights from the latest science on extreme wildfire risk and to provide a thorough review of the multifaceted impacts of wildfires. This provides the basis for informing the discussion on how government policies and practices need to evolve to address future wildfire risk in Chapter 3.

2.2. Understanding wildfire risk

2.2.1. What is a wildfire?

Wildfires are fires that occur in wildland areas such as forests, grasslands and peatlands, and whose occurrence or development is unintended or uncontrolled. They can affect different types of vegetation and behave differently depending on the underlying environmental conditions (Box 2.1). Extreme wildfires are wildfire events (or groups thereof) that are particularly severe in terms of their size, duration, intensity and impacts – which makes them difficult to contain or control (Tedim et al., 2018[20]).[1]

Box 2.1. Defining wildfires

Countries use different terms to refer to wildfires. For example, Australia refers to wildfires as “bushfires”, while the terms “wildland fires” and “forest fires” prevail in the United States and many European countries, respectively. The two key characteristics of wildfires shared by these different terms are that they occur in wildland areas and they are not controlled. This sets them apart from “structural fires”, which start and are limited to the built environment, and “controlled fires”, which are planned vegetation fires carried out in a controlled manner for land management purposes.

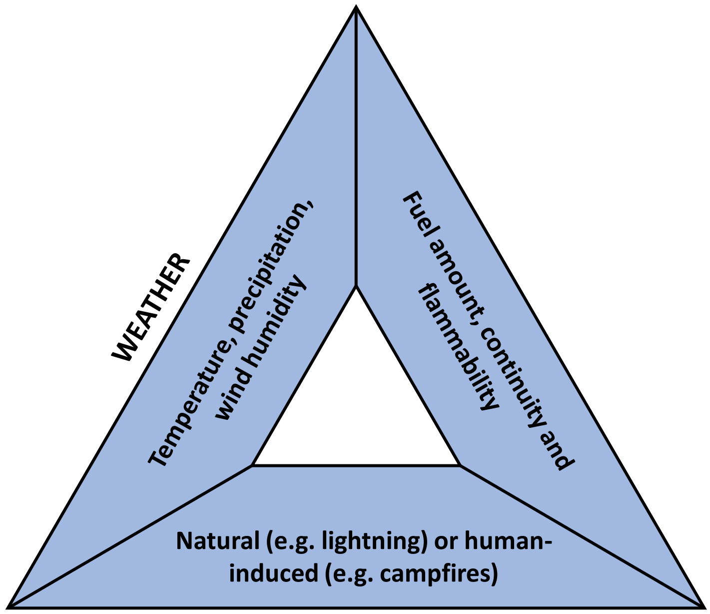
Wildfires can be further characterised by the vegetation they burn:

- *Surface fires* burn surface-level fuels, such as grass and small shrubs, without affecting the top of the trees. These wildfires are the easiest to control and are typically the least damaging.
- *Crown fires* burn trees and their crowns. These are the most intense and difficult to control wildfires, thereby posing a considerable risk to human lives, ecosystems and economies.
- *Ground fires* (or sub-surface fires) occur underneath the land surface, burning deep into organic soils or peatlands through smouldering (i.e. combustion without flame). They are extremely difficult to extinguish and can continue burning through the winter, even under snow cover, and risk reappearing at the surface after the winter, causing new wildfires. They mainly affect the Arctic regions of Alaska, Canada and Siberia.

Sources: Scholten et al. (2021[21]); Weise, Cobian-Iñiguez and Princevac (2018[22]); Government of Canada (2021[23]).

To occur, wildfires need fuel, a source of ignition and meteorological conditions conducive to fire (i.e. fire weather). These three factors, usually referred to as the “fire triangle” (Figure 2.1), affect both wildfire occurrence and behaviour, which describes how wildfires ignite and spread over space and time.

Figure 2.1. The key factors influencing wildfire occurrence



Wildfires need flammable material that provides fuel to the flames (Hincks et al., 2013[24]). While vegetation usually provides most of the fuel for wildfires, flammable buildings scattered in the wildland also contribute to fuel wildfires. For a wildfire to start and develop, fuel needs to be abundant, continuous and sufficiently dry to burn. Fuel flammability depends on fuel type (i.e. its chemical composition and physical structure) and moisture. For example, finer and drier fuels such as leaves and bark burn more readily than living tree trunks and large wood debris. Similarly, oil- and wax-rich fuels, such as eucalyptus leaves and pine needles, are particularly flammable, facilitating the spread and intensity of wildfires (Dimitrakopoulos and Papaioannou, 2001[25]; Guerrero et al., 2022[26]). Once fuel is dry enough to sustain a flame, its energy release usually leads to the further drying of adjacent fuel, facilitating the propagation of the wildfire.

Fire weather consists of a combination of meteorological conditions that are conducive to fire, such as atmospheric temperature, precipitation and relative air humidity, wind speed and lightning activity (Climate Central, 2021[27]; Jones et al., 2022[7]). For example, abundant precipitation in fall or winter facilitates vegetation growth that can fuel wildfires during the following fire season, while scarce precipitation, warm temperatures and strong winds in spring or summer contribute to drying fuels, increasing their flammability (Jones et al., 2022[7]). Strong winds provide oxygen to the fire and accelerate the advancement of the fire front, including by transporting embers (i.e. small pieces of burning fuel carried by the wind), which can ignite new wildfires up to several kilometres ahead of the advancing fire front (Martin and Hillen, 2016[28]). Altogether, fire weather plays a key role in determining when and how a wildfire can spread. Overall, a situation where air temperature exceeds 30°C, wind speed exceeds 30 km per hour and relative humidity falls below 30% is an indicator of particularly risky fire weather conditions (Steffens, 2016[29]).

Wildfire ignition can occur due to natural causes or human activity. Natural ignitions are usually induced by lightning (Yuan, Restuccia and Rein, 2021[30]). For example, the 2020 August Complex wildfires in California, the largest in the state's history, were ignited by lightning (USDA, 2021[31]). Yet, human activity (accidental or due to arson) is the main driver of wildfire ignition and is responsible for nearly 70% of the total burned area globally (Veraverbeke et al., 2022[32]). Human ignitions dominate in urban and rural landscapes, while lightning remains the major ignition source of wildfires setting off in remote areas (Jones et al., 2022[7]). However, the causes of wildfire ignition are not always easy to identify, and, in some contexts, different ignition sources combined can lead to particularly large and complex wildfires. For example, the extreme 2009 Black Saturday wildfires in Australia were caused by a combination of different ignition sources, including lightning, downed power lines and arson (Parliament of Victoria, 2010[33]). While the ignition source of the wildfire is the key element to start the fire, ignition alone is not sufficient to sustain a wildfire. Indeed, in the absence of flammable fuel and fire weather, wildfires do not spread. Conversely, in the presence of abundant and dry fuel and hot and dry conditions, a single spark can be sufficient to start a major wildfire. Hence, understanding the driving factors of wildfire events, and most notably the fuel and weather conditions that facilitate wildfire risk, is critical in the management of wildfires.

2.2.2. From natural fires to the emergence of increasingly extreme wildfires

Different regions and ecosystems are adapted to different patterns of wildfire frequency, size and intensity, which are called fire regimes. For example, the tropical grasslands of South Africa and Northern Australia are usually characterised by large wildfires that occur every one to four years, while temperate and boreal regions in North America and Eurasia are usually subject to higher-intensity wildfires that occur less than every 50 years (Table 2.1) (Archibald et al., 2013[34]).

Table 2.1. Different fire regimes

Fire regime	Ecosystems where they occur	Typical wildfire characteristics
Frequent, intense and large	Grasslands of tropical regions, e.g. Australia, south of Africa, Central America	Frequent (occur every 1-4 years) Intense (350-660 MW) Very large size (around 400 km2)
Frequent, cool and small	Tropical grasslands and savannahs; predominant in the central and southern regions of Africa	Very frequent (occur every 1-2 years) Low intensity (156-253 MW) Rather large size (around 25 km2)
Rare, intense and large	Temperate and boreal regions, e.g. Canada, central and boreal Asia, Mediterranean Europe, north-western United States	Not frequent (occur every 50 years) Very intense (283-844 MW) Large size (around 80 km2)
Rare, cool and small	Temperate and boreal forests in Eurasia	Not frequent (occur every >50 years) Low intensity (108-334 MW) Small size (around 4 km2)
Intermediate, cool and small	Very common; widespread in agricultural areas and areas undergoing deforestation, e.g. tropical forests of Asia and South America, Eastern Europe, the Middle East	Rather frequent (occur every 6-19 years) Low intensity (143-352 MW) Small size (9 km2)

Notes: Size refers to the average extent of burned land. Intensity refers to the rate of energy released by the flames and is measured in megawatts (MW) per 1 x 1 km pixel.
Source: Based on Archibald et al.'s (2013[34]) fire regime classification.

Globally, wildfire activity tends to be higher in areas characterised by enough rainfall to maintain vegetation growth, along with regular dry periods and frequent ignitions that allow fuel to burn (Jones et al., 2022[7]). Conversely, in areas where fuel amounts or flammability are too low to sustain fire (e.g. in deserts and rainforests), as well as in areas where ignitions are not frequent, wildfire activity tends to be naturally lower (Boer et al., 2021[35]; Kelly et al., 2020[36]).

Wildfires are an endemic component of many ecosystems. Ecosystems where wildfire activity has long been present have evolved and adapted to coexist with fire (He and Lamont, 2018[37]). In these fire-adapted ecosystems, wildfires are an essential process that provides important ecological functions, for example by clearing excess vegetation and releasing nutrients (Kumar et al., 2022[38]). Species in these ecosystems may also rely on regular fire activity for their reproduction and development (Hincks et al., 2013[24]). Under normal conditions, these ecosystems recover naturally after a wildfire. Conversely, ecosystems where wildfires are not common, so-called fire-sensitive ecosystems, are not adapted and thus more vulnerable to fire. Understanding local fire regimes and the level of adaptation of each ecosystem to fire is thus fundamental to effectively managing wildfire risk in different areas.

Climate change, coupled with unsustainable land use and management practices, has significantly altered the frequency, size and severity of wildfires in many areas (Kelly et al., 2020[36]), thereby weakening the natural resilience of fire-adapted ecosystems and exacerbating the vulnerability of fire-sensitive ones. Countries not used to frequent or intense wildfire activity, such as Austria, Ireland and Sweden, as well as vast areas of tropical rainforest and the Arctic region, have increasingly experienced wildfire extremes (EEA, 2021[39]; Wotton, Flannigan and Marshall, 2017[40]). Wildfires can have particularly negative impacts in areas where wildfire activity is not endemic. At the same time, areas that are well-adapted and used to a sustained level of wildfire activity have experienced an increase in the frequency and severity of wildfires. This is, for instance, the case for boreal and temperate forests and the Mediterranean region, which – while adapted to fire – have experienced growing challenges in their ability to recover after extreme wildfires (WRI, 2022[41]; Damianidis et al., 2021[42]).

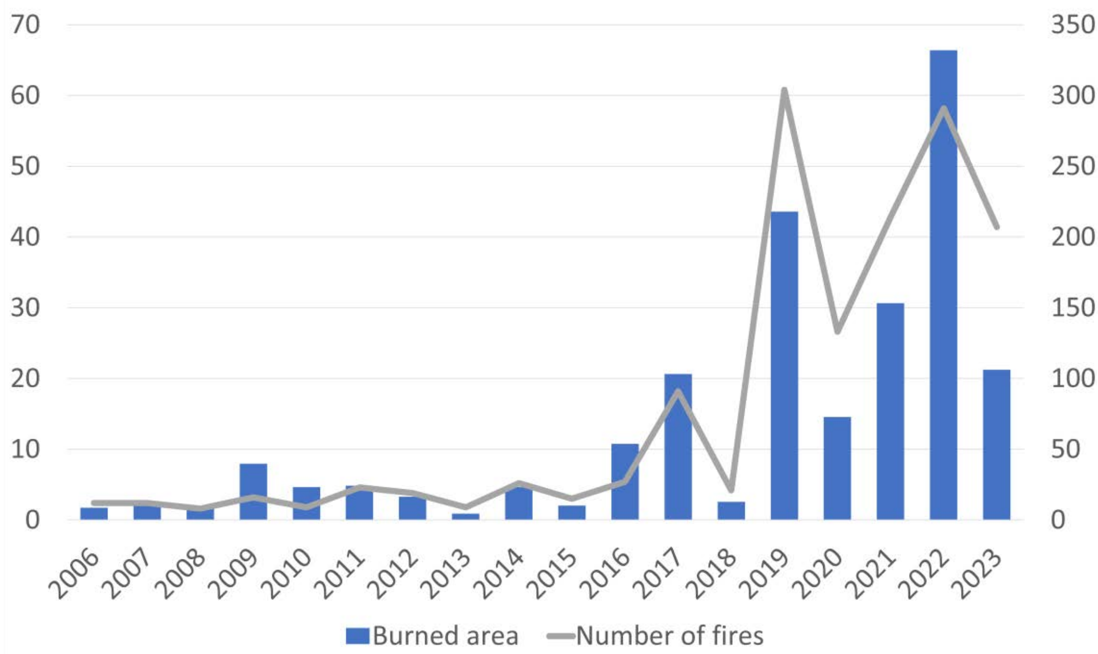
2.3. Observed wildfire trends

Many countries have experienced an increase in the frequency, size and severity of wildfires in recent decades. For example, average wildfire frequency almost doubled in Australia between 1980 and 2020 (Canadell et al., 2021[43]), while in Austria, the number of wildfires in forested lands more than doubled between 1993 and 2020 (Forest Fire Database Austria, n.d.[44]; Institute of Silviculture (WALDBAU), n.d.[45]). The number of large-size wildfires has also substantially increased in many areas, including in France (Figure 2.2) (EFFIS, 2023[46]) and in most regions of the United States (Salguero et al., 2020[47]; Hanes et al., 2019[48]), with the seven largest wildfires ever recorded in California all having occurred after 2017 (Cal Fire, n.d.[6]). Wildfire severity, i.e. the degree of ecosystem impacts caused by a fire, has also significantly increased in some regions, including in Australia and the United States (Tran et al., 2020[49]). For example, in the forests of the western United States, wildfire severity increased eightfold between 1985 and 2017 (Parks and Abatzoglou, 2020[50]; Singleton et al., 2019[51]).

Some countries have experienced substantial increases in the extent of the area burned by wildfires. While globally, area burned has declined over the past decades, largely due to lower fuel loads in the vast African savannahs, in some regions – and most notably in forested areas – area burned has significantly increased (Jones et al., 2022[7]; Doerr and Santín, 2016[52]). Since 1959, the annual average area burned by wildfires has tripled in Canada (Bowman et al., 2020[53]), while burned area in Australian forests increased by an annual average of 800% between 1988-2001 and 2002-19 (Canadell et al., 2021[43]). In the United States, both the number of large wildfires and the area burned every year have significantly increased since 1985. Similar trends are observed across the People’s Republic of China (hereafter “China”); India; and Siberia, Russian Federation (hereafter “Russia”) (Earl and Simmonds, 2018[54]; Ponomarev, Kharuk and Ranson, 2016[55]), as well as in the rainforests of Amazonia and Central Africa (Jones et al., 2022[7]; Jiang, Zhou and Raghavendra, 2020[56]). Increased area burned in forested areas represents a cause for concern, as forest fires tend to have longer-term ecological and climate consequences than grassland areas (Zheng et al., 2021[57]).

Figure 2.2. Change in the extent of burned area and the number of wildfires in France, 2006-23

Thousand hectares burned per year (left axis) and number of wildfires recorded per year (right axis)



Notes: Data retrieved from the European Forest Fire System. It includes fires of approximately 30 hectares or larger.
Source: Based on EFFIS (2023[46]).

The number and recurrence of extreme wildfire events and seasons are also on the rise in some countries. The 2019-20 wildfires in Australia burned between 24 million and 40 million hectares of land (Royal Commission, 2020[1]), while the 2020 wildfires in California, United States, lasted over four months and affected over 400 000 hectares of land, becoming the largest in the state's history (USDA, 2021[31]). The 2018 Camp Fire in the United States caused a loss of nearly 19 000 built structures and an unprecedented USD 19 billion in direct economic damages, becoming the deadliest and most destructive in the state's history (OECD, forthcoming[58]; California Department of Forestry and Fire Protection, 2022[59]; Karels, 2022[60]; Chase and Hansen, 2021[61]; Syifa, Panahi and Lee, 2020[62]).

Extreme wildfire events have highlighted the limits of traditional wildfire management practices and policies in many affected countries (see Chapter 3). To build resilience to extreme wildfire risk in affected countries, it is key to understand the underlying driving forces behind this uptick not only in frequency but also in the extreme nature of wildfires.

2.4. Drivers of extreme wildfires and projections

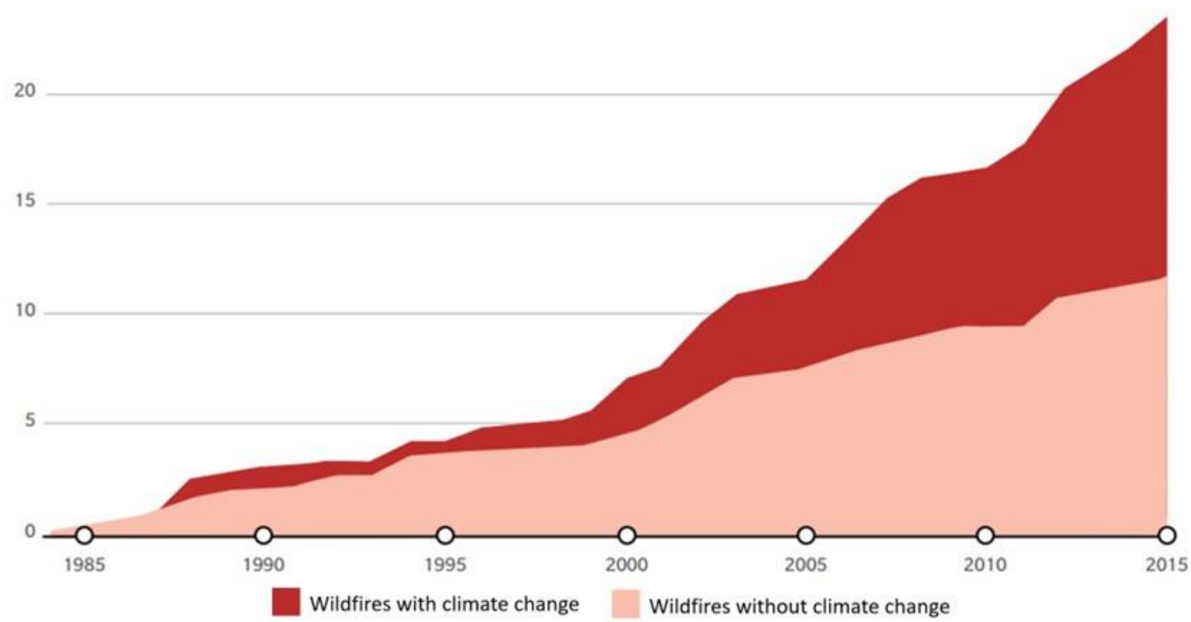
The observed changes in fire activity are driven by a combination of factors. In many cases, climate change exacerbates weather and fuel conditions that make it easier for fires to start and spread. Additionally, land-use and other human-induced changes to the landscape and the fire cycle also play a role in shaping these current trends.

2.4.1. The effects of climate change on wildfire trends

Climate change plays a key and increasing role in determining wildfire regimes (Jia et al., 2019[63]). While the attribution effect of climate change in extreme wildfires was not well established in the past, a significant body of research has emerged in recent years, clearly demonstrating this link. Climate change is estimated to have doubled the total forest area burned in the western United States between 1984 and 2015 (Overpeck, Dean and Stapp, 2018[14]) (Figure 2.3) and to have enhanced wildfire occurrence in mountainous areas (Alizadeh et al., 2021[64]). The extreme fire weather that facilitated the Australia wildfires in 2019-20 was estimated to be at least 30% more likely because of climate change, while the extent of the 2017 extreme wildfires in Canada was 7 to 11 times higher because of climate change (van Oldenborgh et al., 2021[15]; Kirchmeier-Young et al., 2019[16]). A similar link has been established for the 2018 Camp Fire in the United States, where climate change doubled the likelihood of the extreme fire weather that fuelled the wildfire (Park Williams et al., 2019[65]; Goss et al., 2020[66]). Climate change has also been linked to the occurrence of the 2020 extreme wildfires in Arctic Siberia, Russia (Ciavarella et al., 2021[67]).

Figure 2.3. Cumulative forest area burned associated with climate change in the western United States, 1984-2015

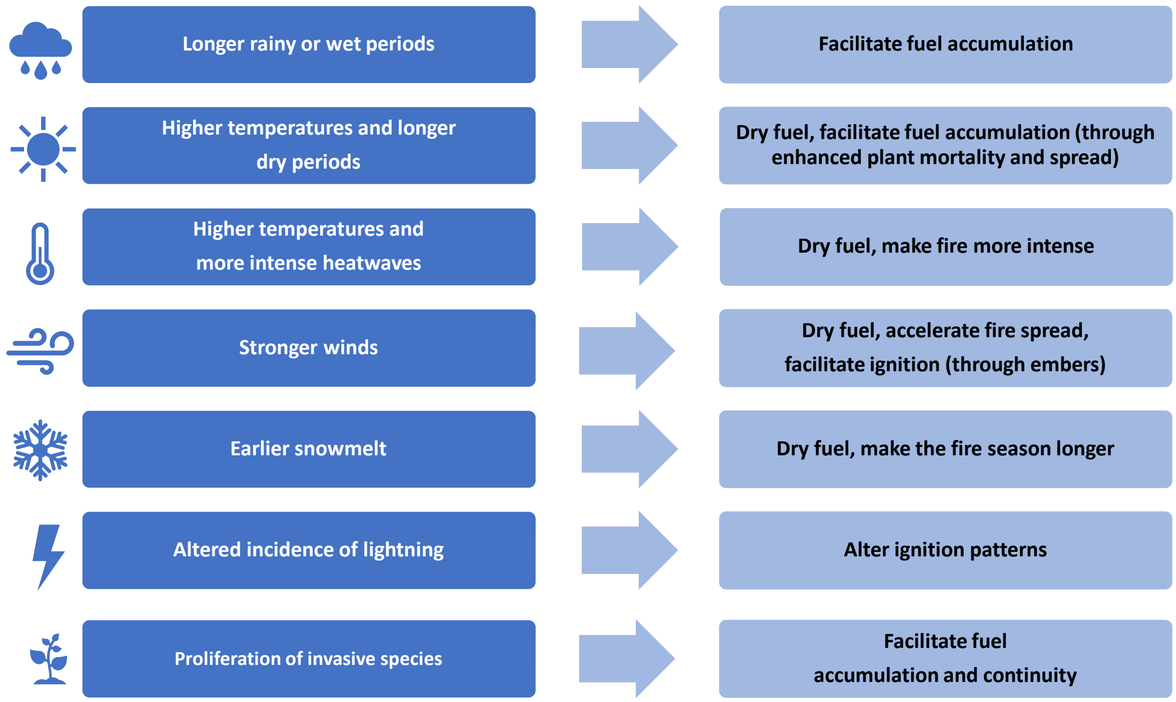
Million acres



Source: Adapted from Marsh & McLennan Companies (2019[68]).

Climate change influences all elements of the fire triangle (Figure 2.1), namely weather, fuel, and ignition, thus playing a key role in determining wildfire frequency, size and intensity (Figure 2.4) (Mahood et al., 2020[69]; Herawati et al., 2015[70]; US EPA, 2022[5]).

Figure 2.4. The links between climate change and growing wildfire risk



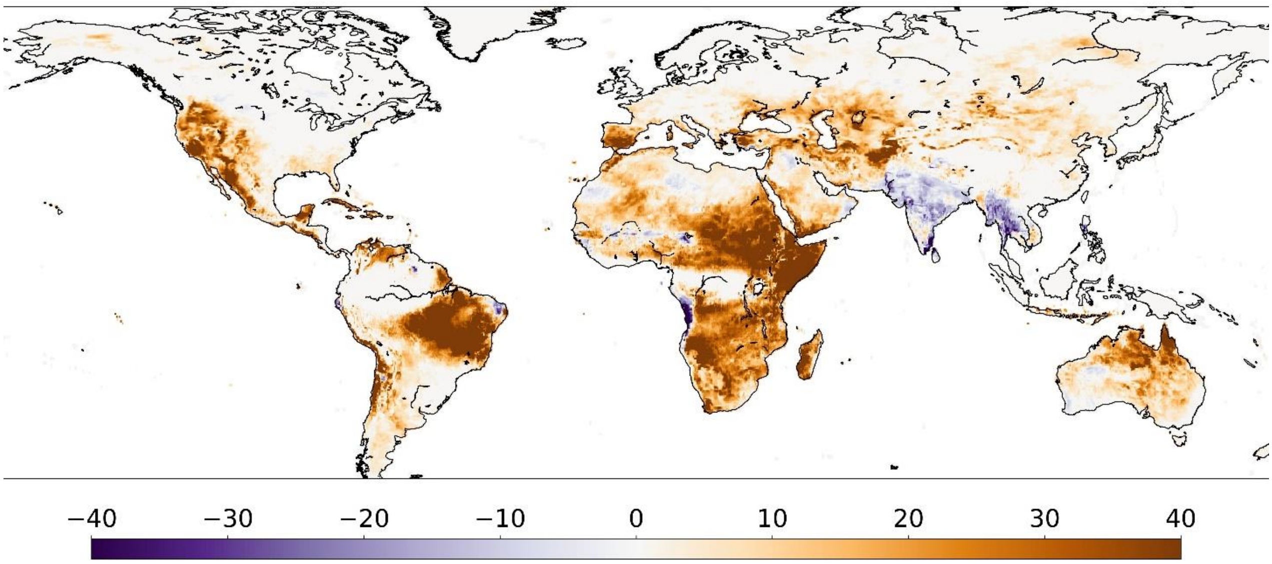
The effects of climate change on fire weather

Climate change affects the likelihood of fire weather. Prolonged wet seasons in some areas can facilitate vegetation growth, while the combination of higher atmospheric temperatures, low precipitation levels, heatwaves and drought contribute to drying the vegetation, enhancing landscape flammability in the wildfire season. For example, drought has been associated with the occurrence of the 2017 wildfires in Chile and Portugal (Turco et al., 2019[71]; Bowman et al., 2019[72]), the 2018 Camp Fire in the United States (Hawkins et al., 2022[73]), and the 2020 wildfires in Arctic Siberia (Ciavarella et al., 2021[67]). It also resulted in a larger burned area in Congo's rainforests between 2003 and 2017 (Jiang, Zhou and Raghavendra, 2020[56]). Exceptionally high atmospheric temperatures were associated with the occurrence of the 2019 Arctic wildfires in Canada (Fazel-Rastgar and Sivakumar, 2022[74]) and the 2018 wildfires in Australia (Lewis et al., 2020[75]). Higher atmospheric temperatures reduce air and soil moisture and facilitate the occurrence of more intense wildfires (Doerr and Santín, 2016[52]), as observed during the 2009 wildfires in Australia (Marsh & McLennan Companies, 2019[68]). Stronger winds under climate change (IPCC, 2022[9]) also contribute to drying fuels while at the same time facilitating the advancement of the fire front. Strong winds were associated with the occurrence of many of the extreme autumn wildfires that affected California in recent years, including the 2018 Camp Fire (Hawkins et al., 2022[73]). Climate change-induced earlier onset of snowmelt facilitates and anticipates soil and vegetation drying and extends the duration of the wildfire season in many areas. The increase in wildfire frequency and duration in the western United States observed over the past decades was largely attributed to early snowmelt (Westerling et al., 2006[76]). Finally, in some cases, climate change can facilitate fire-atmosphere interactions that produce more extreme and particularly unpredictable wildfire behaviour (Castellnou et al., 2022[77]).

Globally, fire weather has become more frequent, longer and more extreme (Holden et al., 2018[78]). The duration of the fire weather season has increased by 27% since 1979, with particularly large increases in its duration recorded in eastern and southern Africa, northern Australia, central Asia, the Mediterranean region, as well as in the Amazon region (Figure 2.5), where the duration of the fire weather season increased by 39 days between 1979 and 2019 (Jones et al., 2022[7]).

Figure 2.5. Change in the duration of the fire weather season, 1979-2019

Change in the number of fire weather days



Notes: Cumulative change in the duration of the fire weather season between 1979 and 2019 based on data from Vitolo et al. (2020[79]) using the ERA5 dataset. Purple areas represent a decrease in the duration of the fire weather season, while brown areas represent an increase.
Source: Adapted from Jones et al. (2022[7]).

The extreme weather observed during the 2019-20 wildfires in Australia was found to be at least 30% more likely due to climate change (van Oldenborgh et al., 2021[15]), while the extreme conditions that preceded the Fort McMurray (or Horse River) wildfire in Canada were estimated to be up to six times more likely due to climate change (Kirchmeier-Young et al., 2017[80]). Climate change-induced fire weather is also estimated to have enhanced fire weather during the 2018 wildfires in Sweden (Krikken et al., 2021[81]). While more analysis is needed to better understand the links between climate change and wildfires, this initial body of research already strongly demonstrates the causal link between climate change and changing wildfire risk.

The effects of climate change on fuel

Climate change alters the amount and conditions of fuel available in the landscape (Halofsky, Peterson and Harvey, 2020[11]). While longer wet seasons tend to increase vegetation growth, extended drought periods and higher temperatures can increase plant mortality, increasing the amount of dead fuel available to burn and making alive fuels such as plant leaves more flammable (Stephens et al., 2018[12]). This was observed in the south-eastern Amazon, where 11% more of forestland was destroyed in 2007 following drought periods than in non-drought years (Brando et al., 2014[82]). Similarly, climate change-induced increases in the proliferation of plant pests and diseases also contribute to plant mortality and thus to the accumulation of dry fuel (Invasive Species Centre, 2022[83]; Gullino et al., 2022[84]). For example, climate change has facilitated the spread of bark beetles in the United States, which affected over 22 million hectares of forested lands, an area the size of Utah (WWF, 2020[85]; Marsh & McLennan Companies, 2019[68]). Tree mortality has been associated with wildfire severity during the extreme 2003 and 2015 wildfires in California (Axelson et al., 2019[86]).

The proliferation of non-native species, facilitated by climate change, can also increase fuel build-up, density and continuity (Invasive Species Centre, 2022[83]). For example, between 2000 and 2015, the expansion of non-native grasses in the United States was associated with up to a 230% increase in regional fire occurrence and up to a 150% increase in wildfire frequency (Fusco et al., 2019[87]).

The effects of climate change on wildfire ignition

Climate change increases the occurrence of lightning strikes and, thereby, wildfire ignitions. For every degree Celsius of atmospheric warming, the number of lightning strikes in the United States is set to increase by about 12% (Romps et al., 2014[10]). The link between lightning and wildfire ignition has already been observed in the boreal forests of Canada and Alaska, United States, where between 1975 and 2014, lightning-induced ignitions increased by 2-5% every year (Hanes et al., 2019[48]; Veraverbeke et al., 2017[88]; WWF, 2020[85]). Under future climate change, lightning activity is projected to increase in most regions of the world, with lightning strikes becoming 50% more frequent in the United States by the end of the century (Jones et al., 2022[7]; Romps et al., 2014[10]). In the Arctic, lightning activity is projected to more than double under a high-emission scenario (RCP 8.5) (Chen et al., 2021[89]).

2.4.2. The effects of human activity on wildfire trends

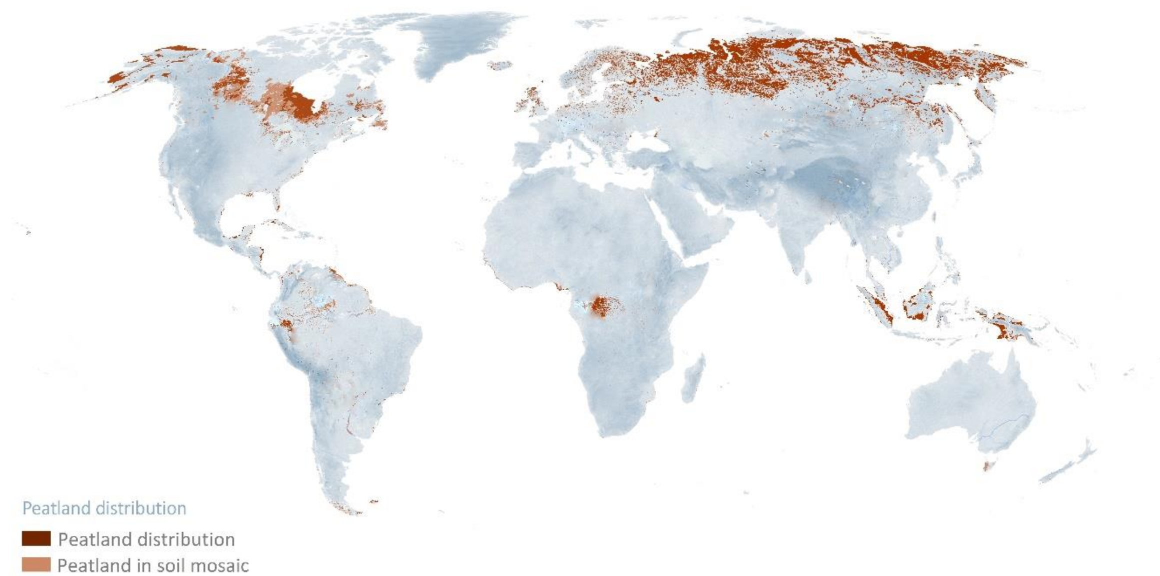
Land use and land management practices in the wildland-urban interface (WUI) and, more broadly, in rural and wildland areas play a key role in determining wildfire occurrence and behaviour, as well as the extent of wildfire impacts. At the same time, development in the WUI, as well as rural depopulation and land abandonment, also affect wildfire occurrence and behaviour (Jia et al., 2019[63]).

Land-use changes and ecosystem degradation

Deforestation, i.e. the conversion of forest land to other land uses, is one of the leading causes of growing wildfire occurrence in some areas, especially in tropical regions. The conversion of forests to other land uses, such as cropland (e.g. oil palm plantations) and grazing areas, has led to a global decrease in forest cover and an increase in forest fragmentation (Austin et al., 2019[90]). These trends are particularly evident in tropical forests, which between 2000 and 2018 accounted for 90% of global deforestation (FAO, 2022[91]). Forest fragmentation contributes to making the landscape more flammable and, in tropical forests, can cause a reduction in local precipitation levels, generating a positive feedback loop between wildfire occurrence and forest loss (Armenteras et al., 2021[92]; Cochrane, 2003[93]; dos Reis et al., 2021[94]). For example, deforestation in Congo's tropical forests is projected to decrease precipitation levels by 8-10% by 2100 (Smith, Baker and Spracklen, 2023[95]). This is exacerbated by the fact that land clearing for land conversion is often achieved using fire, which in some cases can escape control and turn into a wildfire (WWF, 2020[85]). The 2019 wildfires in Amazonia, like most wildfires in the Amazonian tropical rainforest, have been associated with deforestation activities (Kelley et al., 2021[96]).

Peatland drainage is associated with the increasing occurrence of wildfires and their impacts, as dry peat is highly flammable. Globally, peatlands are mostly concentrated in the boreal hemisphere (Figure 2.6). To date, on average, about 12% of global peatlands are drained and degraded (UNEP, 2022[97]). Reduced water levels in peatland areas enhance the occurrence and severity of wildfires, leading to large smoke emissions and carbon losses. This was observed, for example, during the 2015 wildfires in Indonesia, whose occurrence and intensity were associated with low water levels (UNEP, 2020[98]). Peatland fires are also particularly difficult to suppress, as they mostly burn underground (Borneo Nature Foundation, n.d.[99]).

Figure 2.6. Global peatland distribution



Note: UNEP estimations are based on data from the *Global Peatland Database* compiled by the Greifswald Mire Centre.
Source: Adapted from UNEP (2022[97]).

The introduction of non-native vegetation – which can occur accidentally or deliberately – can also alter wildfire activity. This is particularly common when extensive monocultures of flammable species, such as eucalyptus and pine trees, are planted in fire-prone areas (Barquín et al., 2022[100]). For example, during the 2017 extreme wildfires in Chile, plantations of flammable non-native species (mostly pine and eucalyptus) burned more extensively and at a higher severity than the native vegetation (Bowman et al., 2019[72]). Besides, the introduction of invasive species, such as invasive grasses in the arid western United States, has also been associated with higher wildfire activity in the region (Balch et al., 2013[101]).

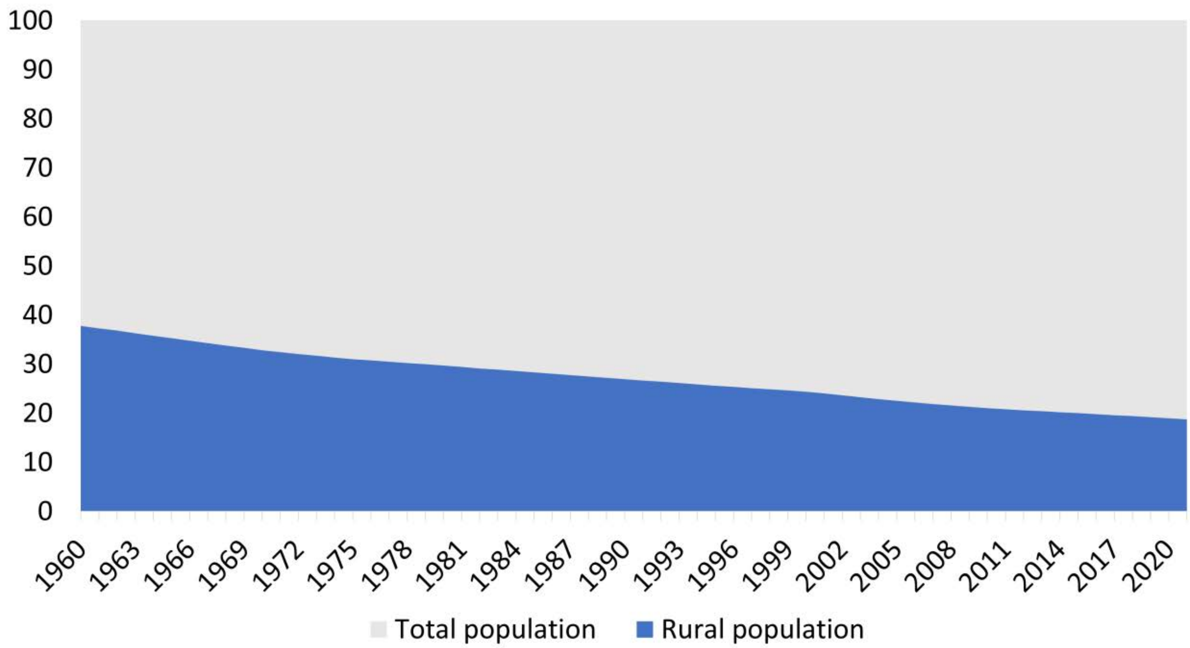
Development in the wildland-urban interface and rural depopulation

The growing expansion of human settlements and economic activities in wildland areas is another core driver of wildfire risk. Globally, the expansion of the WUI, i.e. the area where the built environment and wildland vegetation meet, increases the likelihood of wildfire ignition, which can occur, for example, due to escaped campfires or controlled fires, as well as to faulty infrastructure or engine-induced sparks. For example, the significant growth of WUI areas around the city of Athens, Greece, between 1950 and 1980 has been associated with the high number of wildfires registered in the area (Salvati and Ranalli, 2015[102]). At the same time, WUI development has also increased the exposure of communities, assets and economic activities to wildfires. The effects of WUI development on wildfire activity are particularly concerning as human expansion into the wildland is on the rise. Conversely, in some cases, the intense development of wildland areas can reduce the occurrence and spread of wildfires, as it typically reduces wildfire hazard due to the lower fuel loads and higher fuel fragmentation that characterise agricultural and urban landscapes.

Rural depopulation and the abandonment of traditional land activities such as extensive farming have also led to an increased incidence and severity of wildfires. When rural properties are abandoned and lands are not tended to, vegetation is likely to regrow, increasing fuel loads and thus facilitating the spread of intense wildfires (Aquilué et al., 2020[103]; González Díaz et al., 2019[104]; Pausas and Millán, 2019[105]). These trends (Figure 2.7) are particularly marked in Mediterranean countries, as well as in various eastern European countries (Müller, Vilà-Vilardell and Vacik, 2020[106]). For example, in Portugal, rural population decreased from 5.7 million to 3.4 million between 1960 and 2021, i.e. from 65% to 33% of the total population (OECD, forthcoming[107]).

Figure 2.7. Rural land depopulation in OECD countries, 1960-2020

Percentage share of rural population over total population

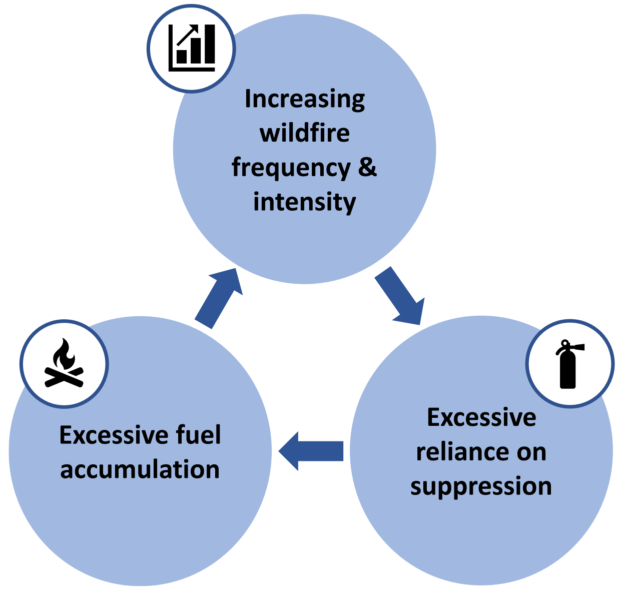


Note: World Bank estimations are based on the *United Nations Population Division's World Urbanization Prospects: 2018 Revision*.
Source: Based on data from the World Bank (n.d.[108]).

Excessive wildfire suppression

The widespread reliance on wildfire suppression in fire management can also amplify wildfire risk. While wildfire suppression is critical to contain the impacts of wildfires in fire-sensitive areas or where population and assets are exposed, suppressing every wildfire without accounting for the needs and characteristics of specific ecosystems can have negative impacts on their balance and increase future wildfire risk. For example, in fire-adapted ecosystems, regular wildfire activity naturally contributes to containing the amount and continuity of vegetation. In these contexts, wildfire suppression can facilitate the excessive build-up of vegetation, which during dry periods can give rise to wildfires that are too large and too intense to contain (Halofsky, Peterson and Harvey, 2020[11]; Williams et al., 2019[109]; Calkin et al., 2014[110]). This is known as the "fire paradox" (Figure 2.8).

Figure 2.8. The fire paradox: The pitfalls of the over-reliance on wildfire suppression



Source: Based on WWF (2020[85]).

2.4.3. Projected changes in wildfire trends

Climate change is projected to continue increasing fire weather, as well as the duration of the fire season and the extent of burned area, contributing to enhancing the occurrence of extreme wildfires in the future.

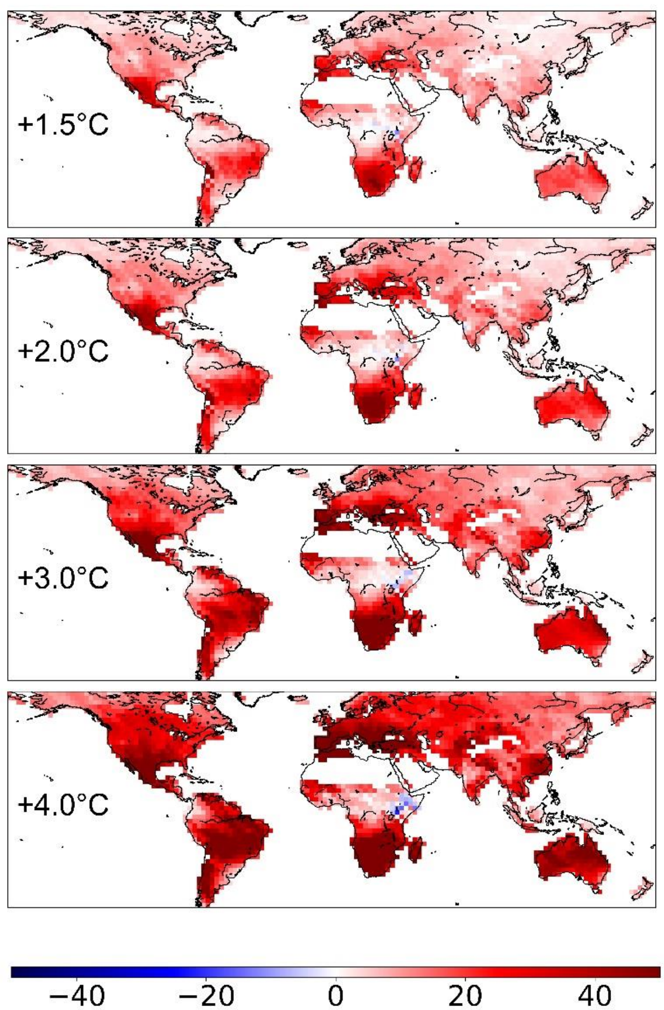
Climate change is likely to increase the occurrence of fire weather conditions on all continents. In south-eastern Australia, extreme fire weather conditions (e.g. periods with high temperatures and wind and low relative humidity and rainfall) are projected to become at least twice as frequent than they are today by 2080 (Herold et al., 2021[111]; Jones et al., 2022[7]). More extreme fire weather conditions are also projected for Indonesia (Jones et al., 2022[7]) as well as for the Mediterranean region, where the frequency of the extreme weather that in recent years has led to extreme wildfires in France, Greece, Portugal and Tunisia is projected to increase by 30% under a high-emission scenario (RCP 8.5) (Ruffault et al., 2020[112]). Under RCP 8.5, the United Kingdom will experience up to a fourfold increase in the number of extreme fire weather days by 2080 (Arnell, Freeman and Gazzard, 2021[113]). Similarly, in the western United States, extreme fire weather is projected to more than double under a +3.0°C warming scenario (compared to pre-industrial levels) (Jones et al., 2022[7]).

The duration of the wildfire season is also projected to increase in most regions of the world. Under a 2°C warming scenario, the duration of the wildfire season is projected to increase by at least 30 days in large parts of South America, Australia, Africa, the western United States, the Mediterranean and the Middle East, northern Europe, and many regions of Asia. Under a high-emission scenario (RCP 8.5), nearly all regions of the world are projected to experience a significant increase in the duration of the wildfire season, with wildfire seasons becoming more than 40 days longer in many parts of the world (Figure 2.9) (Xu et al., 2020[17]; Jones et al., 2022[114]). Amazonia is projected to be one of the most affected regions, with a fivefold increase in the fire season duration under a +4.0°C warming scenario (Jones et al., 2022[7]). Similarly, in Canada, the annual number of fire weather days is projected to increase by up to five times by 2100 under the RCP 8.5 scenario (Wang et al., 2017[115]). As a consequence, many countries are projected to experience a marked increase in wildfire frequency in the future (Xu et al., 2020[17]). Globally, under a 4ºC warming scenario, wildfire frequency is projected to increase by 30% by 2100 (IPCC, 2022[9]).

Area burned is also projected to increase by 19% globally by 2050 compared to 2000, under a moderate-emission scenario (RCP 4.5) (Zou et al., 2020[116]), though this figure is higher in many regions. For example, in the western United States, the average annual area burned is projected to increase by 54% by 2050 compared to 2000, under a business-as-usual (A1B) emission scenario (Spracklen et al., 2009[117]). In Canada, climate change-induced strong winds are projected to increase area burned by 64% by 2050, as compared to 1981-2000 (Marsh & McLennan Companies, 2019[68]). When climate effects on vegetation are also considered along with its effects on weather parameters, existing models forecast up to a 58% increase in global burned area by 2100 (Kloster and Lasslop, 2017[118]). In most cases, however, these projections only account for the projected effects of future climate change on wildfire activity. While demographic and land-use changes will also play a significant role in determining future wildfire activity (Knorr, Arneth and Jiang, 2016[119]; Wu et al., 2021[120]), these human factors are particularly complex to model.

Figure 2.9. Projected change in the duration of the fire weather season under climate change

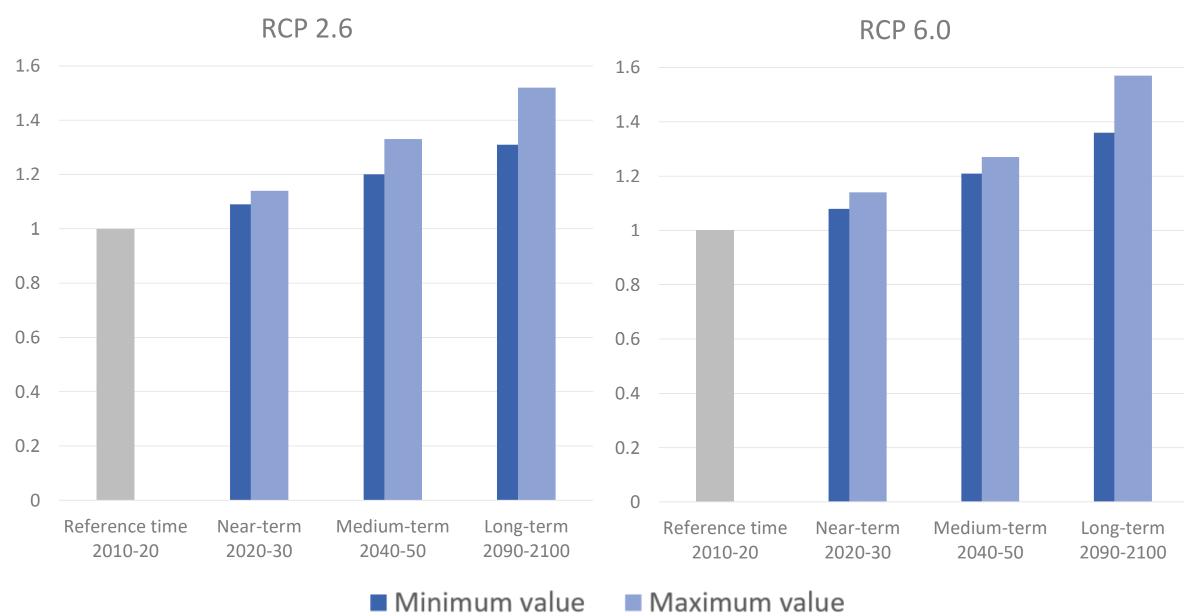
Change in the number of fire weather days, compared to 1860-1920



Note: Projected changes are provided under different degrees of atmospheric warming (+1.5°C, +2.0°C, +3.0°C and +4.0°C) above pre-industrial levels.
Source: Adapted from Jones et al. (2022[114]) based on Jones et al. (2022[7]).

All factors combined, climate change is expected to significantly increase the likelihood of extreme wildfires in the future. This increase is projected to occur even under a low-emission (RCP 2.6) and a moderate-emission scenario (RCP 6.0) (Figure 2.10) (UNEP, 2022[13]).

Figure 2.10. Global likelihood of future extreme wildfire events under different climate scenarios



Notes: RCP 2.6 represents a low-emission scenario while RCP 6.0 represents a moderate-emission scenario.
Source: Based on UNEP (2022[13]).

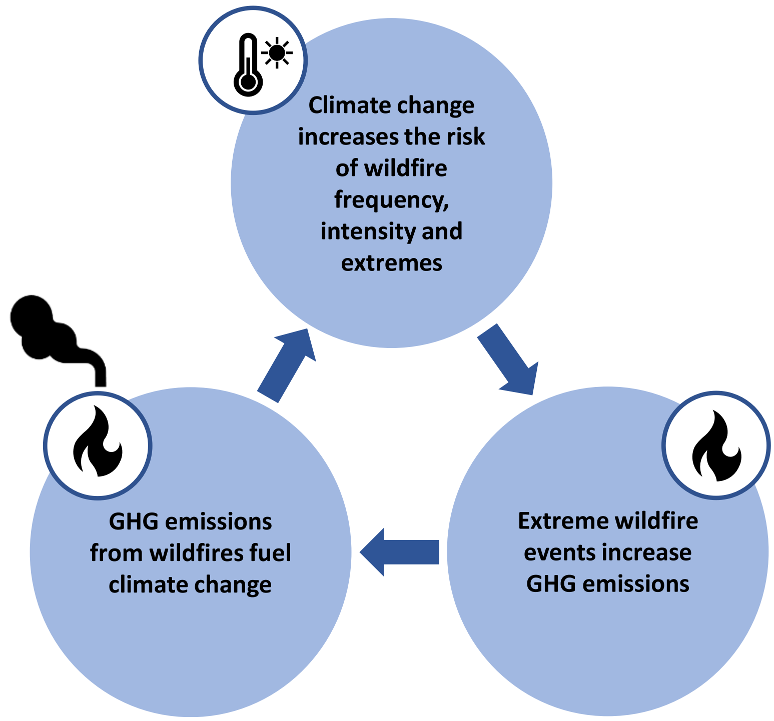
2.5. Understanding the environmental and socio-economic impact of wildfires

Understanding the environmental, social and economic costs of wildfires is essential to characterise wildfire risk and mobilise resources for preventing and managing wildfire risks and impacts. Much of the impacts and costs observed during recent extreme wildfires have been driven or amplified by climate change – a driver that will continue to increase wildfire risk in the future (see Section 2.4.3). In light of growing wildfire risk, governments are under pressure to avoid or at least minimise future impacts and costs. Due to the complexity of the environmental and socio-economic impacts of wildfires, there is limited information on the total costs caused by wildfires at the global level. However, a growing number of studies has shed light on the impacts of wildfires on the climate system (see Section 2.5.1), the environment (see Section 2.5.2), humans (see Section 2.5.3) and the economy (see Section 2.5.4). Last but not least, public spending on wildfire management has also increased to match the growing incidence of wildfire extremes (see Section 2.5.5).

2.5.1. Wildfire impacts on the climate system

While human activities and climate change affect wildfires, wildfires, in turn, affect the climate system by, among other effects, releasing carbon into the atmosphere. Globally, wildfires and controlled fires together emit on average 8 billion tonnes of carbon dioxide (CO_2) into the atmosphere every year, which is equivalent to about one-quarter of the global annual emissions from the combustion of fossil fuel (van der Werf et al., 2017[121]). Under normal conditions (i.e. when wildfires occur as part of natural fire regimes), wildfires have a limited net influence on the global carbon cycle, as most emissions are reabsorbed by vegetation (Jones et al., 2019[122]; Bowman et al., 2019[72]). Yet, extreme wildfires can alter this balance, emitting more carbon than is sequestered by vegetation (MacCarthy et al., 2022[123]; Friedlingstein et al., 2019[124]; Zheng et al., 2021[57]).[2] As shown in Figure 2.11, these greenhouse gas (GHG) emissions from wildfires can fuel climate change, which in turn can further increase the frequency, size and severity of wildfire events, creating a feedback loop between climate change and extreme wildfires (UNEP, 2022[13]).

Figure 2.11. The feedback loop between climate change and extreme wildfires

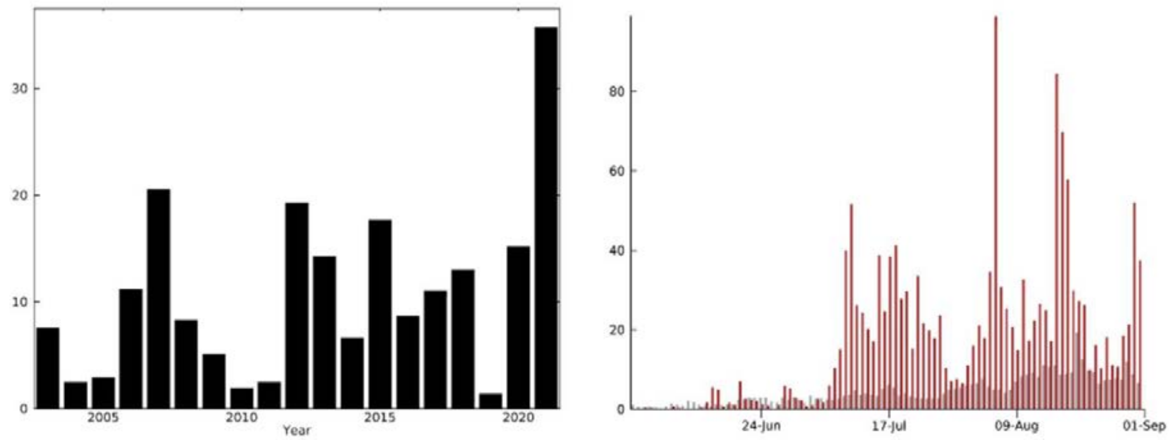


Note: GHG: greenhouse gas.
Source: Based on WRI (2022[41]).

Single extreme wildfire events and seasons have released unprecedented amounts of carbon dioxide from vegetation and soil into the atmosphere (WWF, 2020[85]) (Figure 2.12). This was observed, for example, during the 2019-20 wildfires in Australia, when CO_2 emissions were eight times higher than in the average wildfire season in the past two decades (Li, Zhang and Kondragunta, 2021[125]). In Portugal, the extreme wildfires of 2003 and 2005 – similarly to those of 2016 and 2017 – brought the land-use and forestry sector to emit more carbon than it absorbed, reverting a trend in place since 1991 (OECD, forthcoming[107]; APA, 2017[126]; 2022[127]). In 2017, extreme wildfires brought this sector to account for 23% of Portugal's total emissions (APA, 2022[127]). In 2020, wildfire emissions in California – which amounted to 127 million metric tonnes of CO_2 equivalent – were two times higher than the total GHG emissions reductions achieved as part of the state's climate mitigation efforts between 2003 and 2019 (Jerrett, Jina and Marlier, 2022[128]). Along with higher wildfire intensity, growing wildfire emissions are also due to increasing wildfire activity in forests and peatlands. Carbon emissions from boreal forest fires have been increasing since the year 2000, reaching a new record in 2021, when they accounted for 25% of global emissions from wildfires (Zheng et al., 2023[129]). Extreme wildfires in tropical peatlands and forests account for large shares of overall GHG emissions (Page et al., 2002[130]), posing significant challenges to global climate mitigation efforts and highlighting the urgency to prevent extreme wildfires in forests and peatlands globally. For example, in Indonesia, the 2015 extreme wildfires resulted in approximately 1.6-1.8 gigatonnes of GHG emissions, i.e. over 70% of Indonesia's total GHG emissions that year (Glauber et al., 2016[131]; GFED, n.d.[132]).

Figure 2.12. Wildfire-induced CO_2 emissions in the western United States throughout the fire season

Wildfire-induced carbon emissions (Megatonnes) and daily total fire radiative power (GW)



Notes: Left panel: Estimated carbon emissions for the period June-August in the years 2003-21. Right panel: Daily total fire radiative power for the period June-August 2021. Data from Copernicus Atmosphere Monitoring Service (CAMS), European Centre for Medium-Range Weather Forecast.
Source: Adapted from Copernicus (2021[133]).

At the same time, extreme wildfires can facilitate the degradation of carbon sinks such as forests and peatlands, reducing land carbon storage capacity and thus further hampering global climate mitigation efforts (Nikonovas and Doerr, 2023[134]). This occurs especially when wildfires are too frequent or intense to allow for full vegetation recovery (Friedlingstein et al., 2019[124]). As wildfire frequency and severity are increasing in many regions of the world, including in areas where vegetation recovery and carbon reabsorption are slow or absent (e.g. peatlands), the overall land ecosystems' capacity to reabsorb the carbon emitted during wildfires is decreasing (Zheng et al., 2021[57]; van der Werf et al., 2017[121]). For example, following the 1998 extreme wildfires in Russia, 2 million hectares of forest (i.e. over twice the surface of Portugal) lost their carbon storage capacity for at least a century (WWF, 2020[85]). Future wildfires are projected to reduce land carbon storage capacity in the United States by approximately 0.5 billion metric tonnes by the end of the century (Mills et al., 2015[135]).

In addition, increasing wildfire activity in boreal forests in Canada, Russia, Scandinavia and the United States has contributed to permafrost thaw by increasing soil temperatures, removing the insulating cover of vegetation and organic matter and hampering tree cover recovery (Li et al., 2021[136]; Miner et al., 2022[137]). Besides, the charcoal left behind by wildfires darkens permafrost surface, further enhancing its thaw (Beurteaux, 2022[138]). These processes facilitate heat penetration deeper into the ground (Li et al., 2021[136]), contributing to reducing permafrost thickness and spatial extent (Lawrence et al., 2012[139]). In the boreal hemisphere, permafrost stores one-third of the global soil organic carbon stock. With permafrost thaw, this carbon is likely to be released into the atmosphere without the possibility of being reabsorbed (Mack et al., 2004[140]; Miner et al., 2022[137]). While permafrost can cope with fire to some extent, increasingly extreme wildfires in boreal forests and peatlands accelerate its thaw, enhancing the positive feedback between permafrost carbon release and atmospheric warming (Li et al., 2021[136]) that could lead to an irreversible tipping point (OECD, 2022[141]).

Finally, wildfires also affect the climate system by emitting aerosol particles (e.g. black carbon) in the atmosphere. While suspended, aerosols scatter or absorb solar radiation, affecting global warming, whereas once they deposit on land, they darken snow and ice cover, exacerbating the impacts of climate change (Jiang et al., 2020[142]). These impacts can have far-reaching consequences that go beyond the place and time where wildfires occur. For example, when smoke from the 2019-20 Australia wildfires reached New Zealand, soot deposition darkened the snow cover, accelerating its melting. This acceleration was estimated to be equivalent to that caused by a ~1.8°C increase in atmospheric temperatures (Pu et al., 2021[143]).

2.5.2. Wildfire impacts on the environment

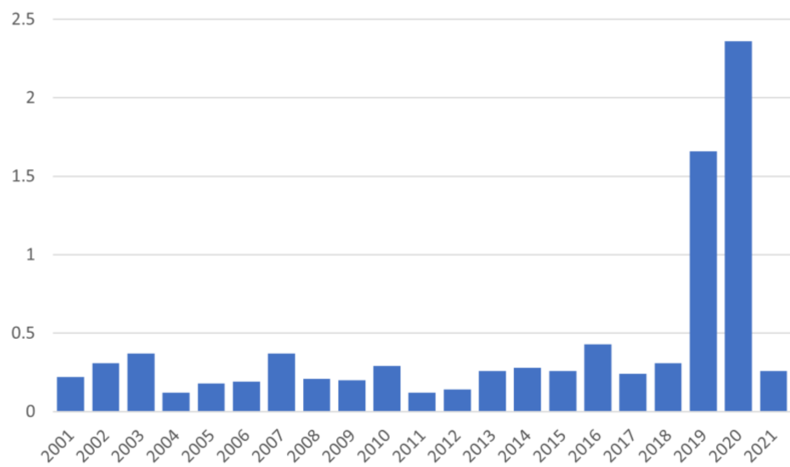
Changing wildfire patterns are increasingly affecting biodiversity, soil, and water availability and quality. Wildfire impacts vary significantly from one area to another, as different ecosystems are adapted to different wildfire regimes, i.e. to specific long-term patterns of wildfire activity. In some ecosystems, such as savannahs, grasslands, boreal and temperate forests, wildfires are a natural and regular component that provides important ecological functions. Species in these ecosystems may rely on regular fire activity for their reproduction and development (Hincks et al., 2013[24]). In such fire-adapted ecosystems, ecological recovery occurs naturally after a wildfire. However, ongoing changes in climate and land cover patterns, together with ecosystem degradation, are affecting natural fire regimes, making it increasingly difficult for these ecosystems to cope with increasingly frequent and severe wildfires (Kelly et al., 2020[36]; Turner et al., 2019[144]). At the same time, due to climate and land-use changes, wildfires also increasingly affect ecosystems where wildfire activity is rare, such as tropical rainforests, where wildfire resilience is low (Lang and Moeini-Meybodi, 2021[145]). In these ecosystems, wildfires are likely to generate long-term biodiversity losses and potentially irreversible ecosystem changes. For this reason, understanding fire regimes and ecosystem needs in different areas is critical for assessing the nature and impacts of specific wildfire events and informing decisions on how to manage them.

Impacts on ecosystems

The growing incidence of extreme wildfires has shown the negative impacts these events can have on vegetation. Globally, in 2021, wildfires affected 9 million hectares of tree cover, which represents an almost fourfold increase since 2001 (WRI, 2021[146]). Tree cover damage is particularly dire following extreme wildfire seasons, such as the 2019-20 wildfire season in Australia, which in 2020 caused a tree cover damage nine times higher than in 2018 (Figure 2.13) (WRI, 2021[147]). While parts of damaged forests may recover in some instances, the extreme nature of the 2019-20 wildfires in Australia hampered ecosystem recovery, leading to potential long-term impacts on forest cover even in fire-adapted areas (Godfree et al., 2021[148]). Extreme wildfires can also facilitate shifts in vegetation cover, which in some cases can be irreversible (Johnstone et al., 2016[149]). Shifts in tree cover following increased extreme wildfire activity were observed in Alaska's boreal forests (Mack et al., 2021[150]) as well as in other areas of the United States, where burned areas that experienced no vegetation regrowth after a wildfire nearly doubled between 2000 and 2011 (Stevens-Rumann et al., 2018[151]). This is because severely burned areas are often subject to soil erosion and dry conditions, which can hinder the survival and germination of new seeds (National Park Service, United States, n.d.[152]). Besides, extreme wildfires can also facilitate the proliferation of invasive species (Úbeda and Sarricolea, 2016[153]), further hampering ecosystem recovery.

Figure 2.13. Trends of forest damage in Australia, 2001-21

Million hectares of forest area damaged



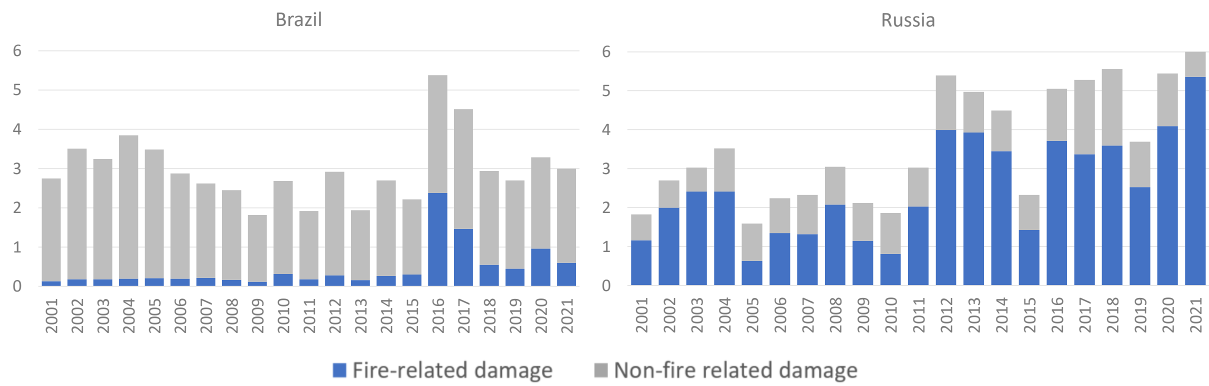
Notes: The peak in forest damage observed in 2019 and 2020 is correlated with the exceptionally large area burned during the 2019-20 wildfire season. While tree cover damage may be permanent in some cases, tree cover damage is temporary in others.
Source: Based on WRI (2021[147]).

When extreme wildfires occur in non-fire-adapted ecosystems, such as tropical rainforests, their impacts on vegetation tend to be longer-lasting and more destructive (Cochrane and Barber, 2009[154]). For instance, in the tropical forests of Indonesia and the Amazon region, extreme wildfires have already contributed to permanent forest loss (Nikonovas et al., 2020[155]; Cochrane and Barber, 2009[154]). In Brazil, burned forest area reached 2.3 million hectares in 2016, which is 11 times more than the average forest area burned in 2001-15 (Figure 2.14) (WRI, 2022[41]). This has contributed to pushing the Amazon rainforest towards a critical tipping point, which, if surpassed, might lead to irreversible shifts in vegetation cover, accelerating global biodiversity loss and the loss of global land carbon storage capacity (OECD, 2022[141]; Boulton, Lenton and Boers, 2022[156]).

Wildfire impacts on vegetation cover and ecosystem processes have been increasingly severe even in ecosystems adapted to fire, such as boreal forests (Turner et al., 2019[144]). Indeed, unusually frequent and intense wildfires do not allow ecosystems to recover in the period between two wildfires, affecting vegetation recovery processes in the long term (Turner et al., 2019[144]; Johnstone et al., 2016[149]). Climate change only exacerbates these impacts. For example, in Russia, the extent of forest area affected by wildfires increased more than fivefold between 2001 and 2021 (Figure 2.14) (WRI, 2021[146]). As a result, in some cases, extreme wildfire activity in fire-adapted forests in Alaska, China and Russia has already been associated with long-term vegetation cover shifts (IPCC, 2022[157]; Mack et al., 2021[150]).

Figure 2.14. Annual forest area burned in Brazil and the Russian Federation, 2001-21

Million hectares of forest area burned



Note: While tree cover damage may be permanent in some cases, tree cover damage is temporary in others.
Sources: Based on WRI (2021[146]; 2022[41]).

The impacts of extreme wildfires on wildlife can also be severe. The combination of fires' high temperatures and flames and associated smoke can cause animal mortality, injury, impairment and displacement. While wildfire impacts on wildlife largely depend on each species' level of adaptation to fire, extreme wildfires increasingly threaten animals' lives and habitats. For instance, following the extreme 2019-20 wildfires in Australia, almost 3 billion animals were killed or displaced (WWF, 2020[158]), while approximately 70 threatened species had up to 50% of their habitat burned (Ward et al., 2020[159]). Similarly, following the 2017 extreme wildfires in Chile, nearly 40% of critically endangered habitats suffered medium to high damage, with severe impacts on biodiversity (FAO, 2020[160]). Freshwater ecosystems were also heavily impacted during the 2019-20 wildfires in Australia, with record fish mortality recorded in estuarine zones downstream of burned areas (Silva et al., 2020[161]).

Whereas evidence on the negative impacts of extreme wildfires on biodiversity is increasing, more systematic records of biodiversity impacts are needed to improve monitoring and inform measures that can reduce fire-related biodiversity loss.

Impacts on soil

Wildfires affect soil properties, composition and stability (Shakesby and Doerr, 2006[162]). The heat from the burning vegetation, along with the combustion of organic matter in the soil, can kill soil biota (i.e. microorganisms, roots, insects and seedbanks) and alter the soil's physical and chemical characteristics, including by reducing its ability to absorb water and retain carbon (Santin et al., 2016[163]). While in most cases wildfire impacts on the soil are limited to the top few centimetres, extreme wildfires can trigger a deeper penetration of heat in the soil, amplifying negative impacts and hampering soil recovery (Santin et al., 2016[163]).

Wildfires can also enhance soil erosion and landslides. Vegetation absorbs the rain and protects the ground from the direct impact of raindrops, preventing soil from being washed away during rainfall. Thus, when wildfires destroy vegetation, burned areas become more prone to soil erosion. This was observed, for example, in Greece, where after the 2018 Attica wildfires, soil erosion rates increased fivefold compared to pre-fire levels (OECD, forthcoming[164]; Efthimiou, Psomiadis and Panagos, 2020[165]). Wildfire-induced erosion is most pronounced in steep terrains, where post-fire rainfall can trigger landslides that can cause fatalities and damages downhill (WWF, 2020[85]). For example, in Tenerife, Spain, the landslides that followed the 2009 wildfires had severe impacts on crops, housing and infrastructure (Neris et al., 2016[166]).

Similarly, in the aftermath of the 2017 wildfires in California, intense rainfall led to the Montecito mudflows, which caused 23 fatalities and destroyed more than 100 houses (Cui, Cheng and Chan, 2018[167]).

Finally, by facilitating erosion, wildfires also affect nutrient distribution in the soil. While this redistribution is a natural process to some extent, extreme wildfires can lead to excessive nutrient transfer. This can hinder vegetation recovery and contribute to water pollution and the loss of soil fertility, as observed in Portugal during recent decades (Shakesby, 2011[168]; Neary et al., 1999[169]; Shakesby and Doerr, 2006[162]).

Impacts on the water system

By affecting vegetation and soils, wildfires can also affect freshwater quality and increase water-related risks (UNEP, 2022[13]). While under normal conditions these risks tend to diminish as vegetation and soils recover their pre-fire conditions (Robichaud, Beyers and Neary, 2000[170]), extreme wildfires challenge ecosystem and soil recovery, exacerbating the duration and extent of such impacts on the water system. To date, 3.5% of the global land surface is subject to high wildfire risk on freshwater security, while almost half of the global land surface is subject to moderate risk (Robinne et al., 2018[171]).

Wildfires affect water quality as a consequence of soil erosion, which facilitates the influx of ash, sediment, carbon, toxic compounds and heavy metals into water bodies (Murphy et al., 2018[172]; Nunes et al., 2018[173]). This can lead to eutrophication (i.e. a reduction in the concentration of dissolved oxygen in water), facilitating algal blooms and fish mortality (Robinne et al., 2020[174]), as observed in the aftermath of the extreme 2019-20 wildfires in Australia (Silva et al., 2020[161]). High nutrient and carbon concentrations in water can also promote bacterial proliferation, and limit bacteria detection and the effective disinfection of water, requiring additional measures and costs for water treatment (Smith et al., 2011[175]). Altogether, the elevated carbon concentrations in water that followed the 2016 Fort McMurray wildfire in Canada led to USD 9 million in additional water treatment expenditures (Emelko et al., 2020[176]). In Colorado, United States, the excessive sediment influx following the 2002 wildfires resulted in USD 60 million in expenditures for reservoir dredging (Robinne et al., 2021[177]).

Extreme wildfires can also exacerbate drought and flood risk. As burned soils tend to absorb less water, groundwater reservoirs tend to recharge less in the aftermath of a wildfire, affecting long-term water availability in certain areas and further hampering post-fire ecosystem recovery. These impacts are further exacerbated by the fact that wildfires often occur during drought periods, during which reservoir levels are already low. In some cases, wildfire-induced water scarcity can manifest itself long after a wildfire has occurred. For example, in Australia, reduced catchment yield following the 1939 wildfires affected the water supply in the city of Melbourne only two to three decades after the wildfire (Kuczera, 1987[178]). This highlights the need to prevent the occurrence of extreme wildfires in key ecosystems such as forests, grasslands and peatlands, which alone provide about 60% of the water supply to the world's 100 largest cities (Martin, 2016[179]). At the same time, when extreme wildfires are followed by heavy rainfall, lower water retention in burned areas (due to lower vegetation and soil recovery and higher soil water repellence) enhances water runoff, increasing flood risk downstream (Murphy et al., 2018[172]; Shakesby and Doerr, 2006[162]). This was observed after the 2007 wildfires in Greece, which increased flood risk for up to ten years after the event (WWF, 2020[85]; Diakakis et al., 2017[180]; OECD, forthcoming[164]). Similarly, after the 2019-20 wildfires in Australia, the combination of extreme wildfires and rainfall caused major floods, along with water pollution (Kemter et al., 2021[181]).

2.5.3. Wildfire impacts on humans

Extreme wildfires in recent years have taken an unprecedented toll on human well-being, both in terms of physical and mental health.

Physical health impacts

The growing incidence of extreme wildfires has increased wildfire-induced fatalities. The 2018 Mati wildfire in Greece took over 100 lives in a single event, while during the 2009 extreme wildfires in Australia, 180 people lost their lives (Table 2.2) (EM-DAT, 2023[2]). The number of wildfire-induced fatalities varies largely depending on the characteristics of the fire as well as of the area where the wildfire occurs. Humans are most exposed to fires in the WUI areas (Box 2.2), which is where most fatalities are recorded (Haynes et al., 2020[182]).

Table 2.2. Extreme wildfires with the highest death toll in the 21st century

Wildfire	Year	Fatalities	Affected population	Total costs (million USD)
Black Saturday wildfires, Australia	2009	180	9 954	1 773
Mati wildfire, Greece	2018	100	4 718	..
Algeria wildfires	2021	90	42 503	..
Camp Fire, United States	2018	88	250 000	19 230
Peloponnese wildfires, Greece	2007	65	5 392	2 470
Portugal wildfires (June 2017)	2017	64	704	277
Russia wildfires	2010	53	5 996	2 416
South Sudan wildfires	2010	50	..	..
Mozambique wildfires	2008	49	3 023	..
Portugal and Spain wildfires (October 2017)	2017	45	2 771	597

Note: Total costs are adjusted to 2021 USD value.
Source: Based on data from EM-DAT (2023[2]).

Yet, the human impacts of wildfires go beyond the lives lost. Wildfires emit particulate matter ($PM_{2.5}$ and PM_{10}), gases and volatile organic compounds that reduce air quality. The impact of wildfires on air quality increases the incidence of respiratory and cardiovascular diseases while also driving the risk of neurological disorders, skin and eye issues, and adverse birth outcomes (Reid et al., 2016[183]; Holm, Miller and Balmes, 2021[184]). In the United States, wildfires are among the main sources of PM pollution (Burke et al., 2021[185]), and today account for 25% of all human exposure to $PM_{2.5}$ and PM_{10} pollution in the country (compared to 5-10% in 2000-05) (Ryan, 2020[186]). Globally, wildfire smoke is estimated to be responsible for 340 000 premature deaths every year related to respiratory and cardiovascular issues, i.e. around 5% of all air pollution-related deaths (WWF, 2020[85]; UNEP, 2022[187]).

The health impacts of wildfires have increased in recent years and have been particularly severe in the aftermath of extreme events. Between 1998 and 2004, wildfires caused a 12% increase in the number of respiratory deaths and a 6% increase in the number of cardiovascular deaths in Greece (Analitis, Georgiadis and Katsouyanni, 2012[188]; OECD, forthcoming[164]). In Brazil, between 2008 and 2018, wildfires were associated with a 21-23% increase in respiratory and circulatory hospital admissions (Requia et al., 2021[189]). The 2015 wildfires in Indonesia caused 100 000 additional deaths, as well as acute respiratory infections for over 500 000 people (Uda, Hein and Atmoko, 2019[190]; Edwards et al., 2020[191]). Similarly, the 2012 wildfires in South America caused 17 000 premature deaths across the western Amazon region (UNEP, 2022[13]). Overall, children, the elderly, and people with disabilities or in social isolation are more vulnerable to the health impacts of wildfires. This was observed, for example, in Paradise, United States, where a higher mortality toll was observed among the elderly and socially isolated population (Verzoni, 2019[192]). With increasing wildfire activity and growing human exposure (Box 2.2), the health impacts of wildfires are projected to increase further in the future (Reid and Maestas, 2019[193]). For example, premature mortality due to wildfire-induced air pollution is projected to double by the middle of the century (compared to 2000) in Canada, Mexico and the United States (Ford et al., 2018[194]).

Mental health impacts

The psychological impacts of extreme wildfires can also be significant. The traumatic experience of being caught in a wildfire, along with the displacement of populations and the loss of homes and personal belongings, can lead to long-term mental health issues such as post-traumatic stress disorder (PTSD), anxiety, depression and insomnia (UNEP, 2022[13]; Rifkin, Long and Perry, 2018[195]). High rates of PTSD, anxiety and depression were observed in the aftermath of the 2018 wildfires in California (Silveira et al., 2021[196]), as well as after the 2016 extreme wildfires in Alberta, Canada, where 60% of the evacuees experienced PTSD (Belleville, Ouellet and Morin, 2019[197]).

Extreme wildfires can also have significant impacts on whole communities, leading to the temporary or permanent displacement of families and social networks and disrupting social activities. For example, the 2016 Fort McMurray wildfires in Canada led to the evacuation of nearly 90 000 people (FAO, 2020[160]), while the 2019-20 wildfires in Australia resulted in more than 70 000 registered evacuations, leading to longer-term displacement for more than 8 000 people (du Parc and Yasukawa, 2020[198]). Overall, in 2020, wildfires were responsible for the displacement of approximately 1.2 million individuals globally, as opposed to approximately 528 000 in 2019 (IDMC, 2020[199]; 2021[200]). The 2015 wildfires in Indonesia also resulted in school closures for over one month, affecting almost 5 million students (Glauber et al., 2016[131]).

Whereas limiting wildfire-induced fatalities requires adapted emergency preparedness and response capacities, the more silent human health consequences can only be reduced by limiting the outbreak and intensity of wildfires through prevention measures *ex ante* (see Chapter 3).

2.5.4. Wildfire impacts on the economy

Macroeconomic impacts

The macroeconomic costs of wildfires result from a combination of the direct costs (e.g. lost and damaged assets, wildfire suppression costs, etc.) and the indirect costs (e.g. lost tax revenue, reduced property values, business interruptions, reduced productivity, recovery costs, etc.) (WFCA, 2022[201]). While comprehensive studies on the macroeconomic impacts of extreme wildfires remain scarce, growing evidence shows that these impacts are high and likely to increase in the future.

Between 2000 and 2017, wildfires are estimated to have caused an average of EUR 3 billion of direct economic losses per year in the European Union and USD 2.3 billion in the United States (Marsh & McLennan Companies, 2019[68]). Yet, single extreme wildfire events can result in significantly higher costs. Between 1980 and 2021, the United States experienced 20 wildfire events that each caused economic damages of over USD 1 billion (US EPA, 2022[5]; NCEI, 2023[4]). For example, the 2018 Camp Fire in California caused an unprecedented USD 19 billion in direct economic damages (OECD, forthcoming[58]; California Department of Forestry and Fire Protection, 2022[59]). Similarly, the 2019-20 wildfires in Australia caused USD 23 billion in direct economic damages (EM-DAT, 2023[2]), becoming the costliest in the country's history (Read and Denniss, 2020[202]). The economic impact of the extreme 2009 Black Saturday wildfires in Australia were estimated at AUD 4.4 billion (Filkov et al., 2020[203]), while the 2007 extreme wildfires in Greece caused a total estimated cost of around 3 billion (Hellenic Republic, 2021[204]; OECD, forthcoming[164]). In Canada, the 2016 Fort McMurray wildfire reduced Canada's GDP by almost 0.5% (i.e. USD 4.6 billion) in the second quarter of 2016 (OECD, 2019[205]), while the regions affected by wildfires in Greece, Italy and Spain have experienced up to 4.8% contraction in GDP growth (Meier, Elliott and Strobl, 2023[206]). In Indonesia, the economic losses associated with the 2015 wildfires exceeded USD 16 billion, i.e. approximately 2% of the country's GDP (UNEP, 2022[13]; Glauber et al., 2016[131]).

Estimates suggest that future wildfire-induced economic costs will increase significantly. By some estimates, wildfires are projected to cost the global economy up to USD 300 billion annually by 2050. In the United States alone, they would result in costs of up to USD 62.5 billion annually (Howard, 2014[207]). While more work is needed to estimate the macroeconomic impacts of wildfires, selected cost assessments, for example for built assets (including houses and infrastructure) or selected economic sectors, provide interesting, yet partial, pictures.

Impacts on built assets

Extreme wildfires have a growing impact on public and private properties such as houses, infrastructure and other built assets. The 2018 Camp Fire in California caused the loss of nearly 19 000 built structures, including roughly 14 000 houses (Karels, 2022[60]; Chase and Hansen, 2021[61]). More than 2 000 houses were destroyed during the 2016 Fort McMurray wildfires in Canada (CDD, n.d.[208]), while during the 2019-20 wildfires in Australia, this figure surpassed 3 000 (Richards and Brew, 2020[209]). Overall, between 1999-2009 and 2009-19, wildfires became more destructive in the western United States, resulting in a 250% increase in destroyed built assets (Higuera et al., 2023[210]). In addition to direct property losses and damages, wildfires can also decrease the value of properties located in high-risk areas. In the United States, this decrease is estimated at 10-20% on average (WWF, 2020[85]). This can reduce the wealth of the property owners and result in a decrease in the tax base and sales. For instance, after the 2013 wildfires in California, property values in the vicinity of the burned areas declined by up to 17% (Batker et al., 2013[211]).

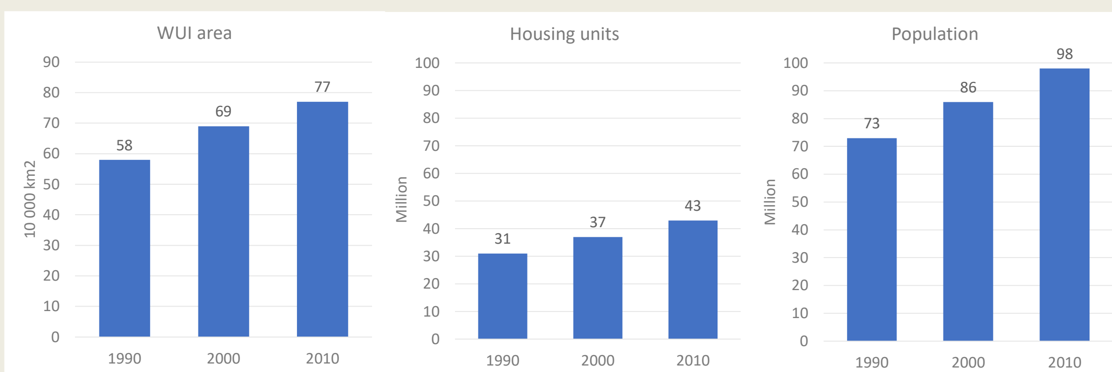
Infrastructure assets and networks have also been severely impacted by recent extreme wildfires, causing disruptions to service provision and continuity, and thus negatively affecting whole communities and economies. While estimates on the costs associated with infrastructure loss and damage remain limited, evidence from recent extreme wildfires shows the large socio-economic consequence of wildfire impacts on critical infrastructure. For example, the costs associated with lost or damaged network infrastructures after the 2017 Portugal wildfires neared EUR 100 million (San-Miguel-Ayanz et al., 2020[212]), while the economic losses resulting from power cuts during the 2007 Tatong wildfire in Australia were estimated at AUD 234 million (Marsh & McLennan Companies, 2019[68]).

These impacts and costs are largely associated with the high and growing exposure of assets to wildfires. Indeed, while on the one hand wildfire frequency and intensity tend to increasingly threaten assets, on the other, the expansion of the WUI in many areas has exacerbated wildfire risk (Box 2.2). To date, in the United States, various states have at least 15% of their properties exposed to extreme wildfire risk, with Montana and Idaho having over one-quarter of their total housing stock at risk of extreme wildfires (Lynch, McMahon and Sassian, 2019[213]). In light of the growing wildfire risk, the costs associated with wildfire impacts on built assets are projected to grow. For example, in Louisiana, United States, average annual property losses due to wildfires – which were estimated at USD 5.6 million in 1992-2015 – are projected to double by 2050 (Mostafiz et al., 2022[214]). This highlights the need to adapt land use and building development to the growing threats posed by wildfires.

Box 2.2. Growing exposure to wildfires in wildland-urban interface areas

The socio-economic impacts of wildfires are particularly severe in the wildland-urban interface (WUI), where houses and other assets are built within or near flammable landscapes and are thus highly exposed to wildfire risk. Besides, many WUI areas are also vulnerable to wildfires due to their limited access to evacuation routes, firefighting resources and other emergency services. Yet, WUI development is on the rise in many areas. Between 1990 and 2010, the WUI area in the United States increased by 33%, while the number of houses in the WUI grew by 40% (Figure 2.15), contributing to the devastating wildfire impacts observed in recent years (Radeloff et al., 2018[215]). These figures are even more striking in some areas of the country. For example, in the western United States, WUI areas have expanded by 60% since 1970 (Marsh & McLennan Companies, 2019[68]). To date, in the United States, 50 million homes (i.e. 1 in 3 houses) and 120 million people (40% of the national population) are located in the WUI area, and these figures are only projected to grow in the coming years (Radeloff et al., 2018[215]; FEMA, 2018[216]). In Greece, the substantial WUI growth around the city of Athens has contributed to the devastating impacts of the Attica wildfires in 2018 (Salvati and Ranalli, 2015[102]). While the expansion of WUI areas is expected to continue going forward (Marsh & McLennan Companies, 2019[68]), the growing incidence of extreme wildfires highlights the need to rethink land-use planning to help prevent wildfire impacts and costs (see Chapter 3).

Figure 2.15. Wildland-urban interface (WUI) area, population and number of housing units in the United States, 1990-2010



Notes: The WUI assessments were undertaken by Radeloff et al. (2018[215]) based on US Census data and the US Geologic Survey's NLCD.
Source: Based on Radeloff et al. (2018[215]).

Sources : Davies et al. (2018[217]); de Torres Curth et al. (2012[218]); Ford et al. (2018[194]); Burke et al. (2021[185]); Mercer and Prestemon (2005[219]); WWF (2020[85]); Radeloff et al. (2018[215]) Marsh & McLennan Companies (2019[68]); Salvati and Ranalli (2015[102]); FEMA (2018[216]).

Sectoral economic impacts

Wildfires can cause significant economic impacts on specific economic sectors, including among others forestry and agriculture, tourism, and healthcare. Whereas existing estimates can provide a telling picture of the financial burden posed by specific wildfire events on selected sectors, these figures are difficult to compare due to differences in the cost assessment methodologies used, as well as to different wildfire characteristics.

The forestry sector is among the most affected by wildfires. In 2017, 10% of Chile's commercial plantations were affected by extreme wildfires (FAO, 2020[160]), while in the same year blazes in British Columbia, Canada, burned a year's worth of timber production (Marsh & McLennan Companies, 2019[68]). The economic losses associated with forestry impacts are also large. Timber losses alone reached AUD 600 million following the extreme 2009 Black Saturday wildfires in Australia (Marsh & McLennan Companies, 2019[68]), while after the 2016 wildfires in Florida, United States, forestry losses amounted to USD 5.8-9.8 billion (Thomas et al., 2017[220]). Growing wildfire risk in Greece's forests is projected to increase forestry losses, leading to a total direct cost of EUR 40 million to EUR 80 million annually by 2100 (compared to 2010) under a modest- to high-emission scenario (Bank of Greece, 2011[18]; OECD, forthcoming[164]).

Agricultural losses also tend to be particularly high in the aftermath of wildfires. Between 2008 and 2018, the cumulative wildfire-induced losses in crop and livestock production exceeded USD 1 billion globally (FAO, 2021[221]). Yet, particularly extreme wildfires have pushed this figure up. After the extreme 2009 Black Saturday wildfires in Australia, agricultural losses amounted to 25% of total wildfire costs (AUD 733 million) (Marsh & McLennan Companies, 2019[68]), while this figure reached 30% after the 2015 wildfires in Indonesia (Figure 2.16) (Glauber et al., 2016[131]). Following the 2019-20 wildfires in Australia, crop and livestock losses amounted to USD 2-3 billion, while damages to farm buildings and equipment and the reduction in farmland values were estimated at USD 2 billion, leading to overall sectoral losses of USD 4-5 billion, i.e. 6-8% of agricultural GDP (WWF, 2021[222]). Altogether, during the 2015 wildfires in Indonesia, agriculture and forestry losses combined amounted to over 55% (i.e. USD 8.7 billion) of the total costs (Figure 2.16) (Glauber et al., 2016[131]). During the 2017 wildfires in Portugal, they accounted for nearly 60% (EUR 840 million) of total costs (San-Miguel-Ayanz et al., 2020[212]).

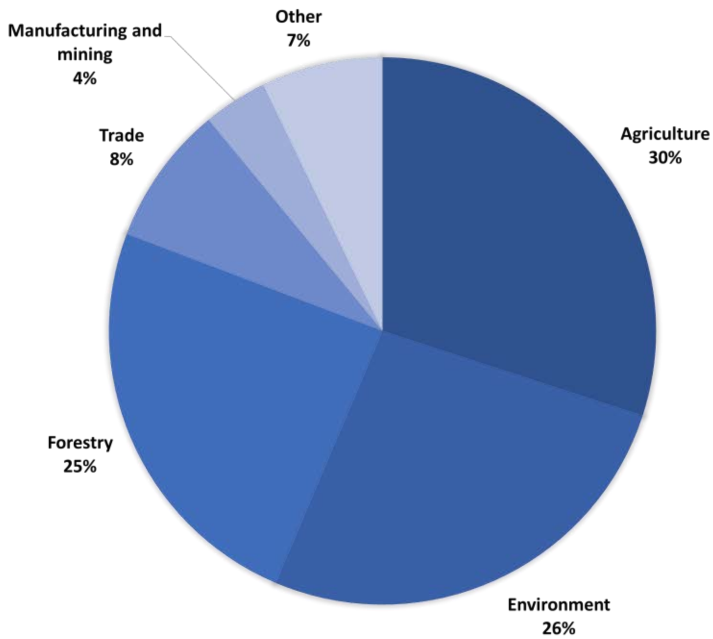
Wildfires can also cause significant economic losses for the tourism sector, as they can affect popular landscapes as well as the attractiveness and reachability of tourist destinations. For example, the 2019-20 wildfires in Australia were associated with tourism losses of USD 3 billion (DW, 2020[223]; WWF, 2020[85]), while in 2015, tourism revenue losses in Indonesia amounted to USD 400 million (Glauber et al., 2016[131]). Such losses are likely to grow in the future in some of the most wildfire-prone touristic regions, such as, for example, Mediterranean countries. For instance, by 2030, Portugal's tourism industry – which today contributes to almost 10% of the country's GDP and employment – is projected to experience annual losses of up to EUR 62 million due to wildfires. In 2050, such losses are projected to at least quadruple (Otrachshenko and Nunes, 2022[19]; OECD, forthcoming[107]).

The health impacts discussed in Section 2.5.3 also translate into significant economic costs for the healthcare sector. For example, the 2015 extreme wildfires in Indonesia were associated with a direct health cost of USD 151 million (Glauber et al., 2016[131]), while the 2019-20 wildfires in Australia caused an additional 4 500 hospital admissions for cardiovascular and respiratory problems and generated overall healthcare costs of nearly AUD 2 billion. This represented a ninefold increase compared to the median cost recorded over the previous 20 years (Ademi et al., 2023[224]). The costs associated with the psychological impacts of wildfires were estimated to have exceeded AUD 1 billion after the extreme 2009 Black Saturday wildfires in Australia (Deloitte, 2016[225]). Whereas estimates on healthcare costs vary significantly, figures suggest that the financial burden of wildfires on the healthcare sector is high and growing.

While the above discussion presents selected estimates of the economic costs induced by wildfires in key sectors, other economic sectors are also affected. For example, the haze generated by the 2015 wildfires in Indonesia affected shipping activities, contributing to losses of more than USD 370 million in the transport sector and USD 1.3 billion in trade services (Glauber et al., 2016[131]).

Figure 2.16. Estimated economic impacts from the extreme 2015 wildfires in Indonesia by sector

Share of total economic loss (billion USD)



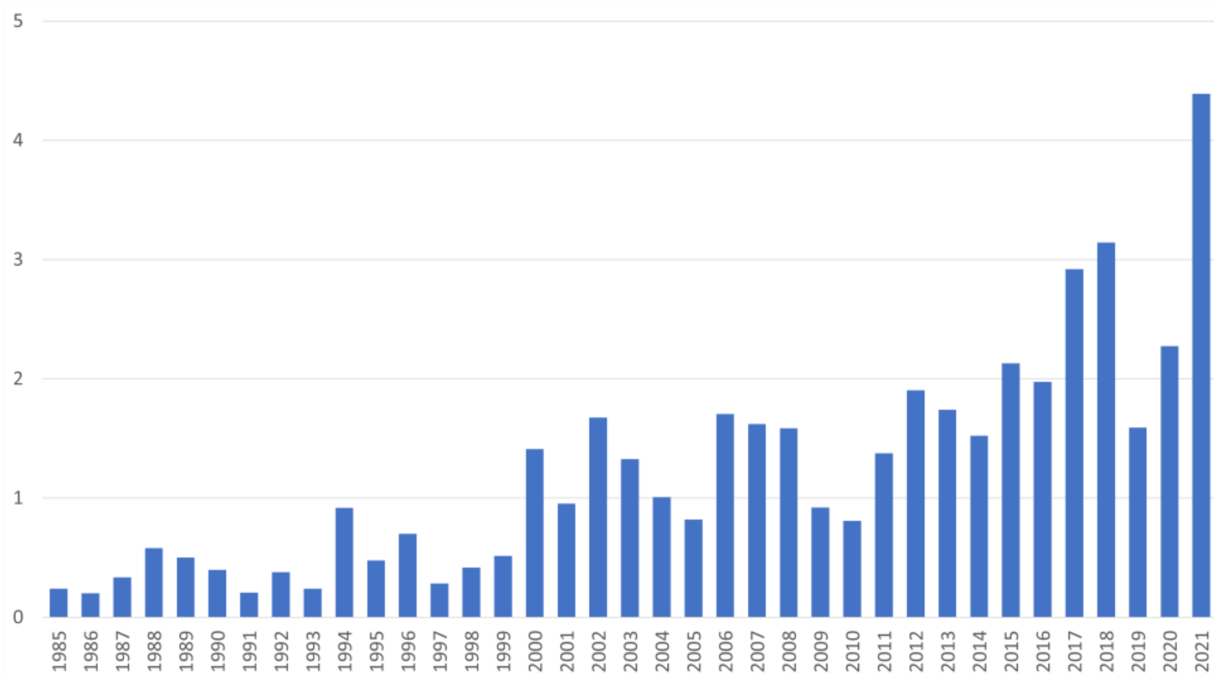
Notes: Percentages show the sectoral share of the total economic losses (i.e. over USD 1.3 billion) recorded between June and October 2015. The category "Other" covers tourism, transport, firefighting costs, health and education. The category "Environment" refers to biodiversity loss and the costs associated with carbon emissions.
Source: Based on data from Glauber et al. (2016[131]).

2.5.5. Public spending for wildfire management

In response to growing wildfire frequency and intensity, countries have scaled up their expenditures for wildfire management. In Canada, the annual costs of wildfire management have increased by CAD 150 million per decade since the 1970s, exceeding CAD 1 billion in 2017 (Natural Resources Canada, 2019[226]). In Portugal, annual wildfire management funding grew by 120% between 2017 and 2021, i.e. from EUR 143 million to EUR 316 million (OECD, forthcoming[107]). In most cases, a large part of this increase in wildfire management expenditures is associated with growing investment in wildfire suppression. For instance, Greece doubled public funding allocated to firefighting between 1998 and 2008 (Xanthopoulos, 2008[227]), while the United States significantly increased federal funding for wildfire suppression (Figure 2.17), from an average of USD 425 million per year in 1985-99 to USD 1.6 billion in 2000-19 (Roman, Verzoni and Sutherland, 2020[228]). In 2021 alone, the United States' federal government spent over USD 4 billion on wildfire suppression (National Interagency Fire Center, n.d.[229]; OECD, forthcoming[58]). In the context of climate change, these costs are only projected to increase in the future (Saha et al., 2021[230]). For example, in Portugal, national funding for wildfire management is set to double by 2030 compared to 2021, reaching EUR 647 million per year by 2030 (AGIF, 2021[231]; OECD, forthcoming[107]).

Figure 2.17. Increase in wildfire suppression costs in the United States, 1985-2021

Billion USD



Note: The chart represents federal costs, including those incurred by the US Fire Service and the Department of the Interior's agencies.
Source: Based on data from the National Interagency Fire Center (n.d.[229]).

Chapter 3 will discuss the need to shift some of that expenditure growth in wildfire management to *ex ante*, wildfire risk prevention measures that address the source of wildfires as opposed to focusing on responding to them. Investments in reducing wildfire risk through vegetation management stand to increase wildfire resilience in the long term.

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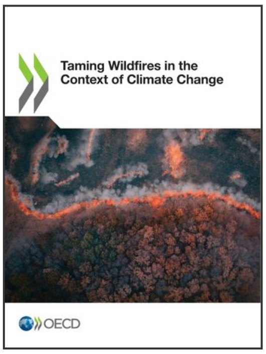
Notes

[1] The exact definition of what is "extreme" largely depends on the fire regimes and specific areas at hand. For example, the US Forest Service identifies extreme wildfires as wildfires that burn more than 40 000 hectares, while in Europe the term has been used to describe smaller wildfires that caused high loss of human lives or other catastrophic socio-economic or environmental impacts (San-Miguel-Ayanz, Moreno and Camia, 2013[232]).

[2] Carbon dioxide (CO_2) emissions account for most wildfire emissions. Wildfires also emit other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) (van der Werf et al., 2017[121]).



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