Taming Wildfires in the Context of Climate Change

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Foreword

Extreme wildfires have repeatedly made headlines in recent years. Fuelled by increasing temperatures, changing precipitation patterns and extended drought periods, extreme wildfires are affecting more and more local communities and regional economies and threatening vulnerable ecosystems across the globe. The 2019-20 wildfires wreaked havoc in Australia, with environmental damages that may well last for decades. The 2018 Camp Fire became the deadliest in California's history and caused economic costs amounting to USD 19 billion, without taking into account the indirect impacts. The consequences of wildfires also go beyond affected countries' borders. Extreme wildfires in the Amazon region, such as those experienced in 2016, may trigger critical tipping points. These could result in abrupt shifts in vegetation cover, which in turn affect global carbon cycles.

As little as a decade ago, there was no way to confirm a clear link between the occurrence of extreme wildfires and climate change, but this has rapidly changed. We now know that climate change alters fire weather and fuel conditions, resulting in a growing number of extreme wildfires. Attribution science has demonstrated that the impacts of the 2017 wildfires in Canada, the 2018 Camp Fire in California and the 2019-20 wildfires in Australia were much greater with climate change than would have been the case otherwise. In the last 30 years, climate change is estimated to have doubled the total forest area burned in the western United States compared to a counterfactual without climate change. Given that further warming is already locked in, this trend will not be reversed anytime soon.

The twin challenges of mitigating climate change and adapting to increasingly extreme wildfires must be tackled together. Managing land and ecosystems sustainably and limiting land development that encroaches on highly exposed wildland areas are key to reducing the impacts of wildfires.

This report, *Taming Wildfires in the Context of Climate Change*, provides a comprehensive global assessment of the links between climate change and growing extreme wildfire risk. It discusses the environmental, social and economic impacts of extreme wildfires and presents emerging country approaches to adapt policies and practices to deal with the growing wildfire risk. As extreme wildfires have demonstrated the limits of wildfire suppression efforts, there is growing recognition of the need to refocus policy efforts on climate change adaptation. Containing future wildfire losses and damages will require integrating preventative actions through a whole-of-government effort. This report provides OECD insights for policy makers and practitioners to help make that happen.

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Abbreviations and acronyms

AGIF	Agency for the Integrated Management of Rural Fires (Portugal) *Agência para a Gestão Integrada de Fogos Rurais*
AUD	Australian dollar
CAD	Canadian dollar
CO_2	Carbon dioxide
EFFIS	European Forest Fire Information System
EU	European Union
EUR	Euro
FEMA	Federal Emergency Management Agency (United States)
GDP	Gross domestic product
GHG	Greenhouse gas
IWUIC	International Wildland-Urban Interface Code
MW	Megawatt
NDC	Nationally Determined Contribution
PM	Particulate matter
PTSD	Post-traumatic stress disorder
RCP	Representative Concentration Pathway
SINAC	National System of Conservation Areas (Costa Rica) *Sistema Nacional de Áreas Protegidas*
USD	United States dollar
WUI	Wildland-urban interface

Executive Summary

The frequency and severity of wildfires, as well as the duration of the fire season, are increasing in many regions of the world. The occurrence of extreme wildfires – i.e. wildfire events that are particularly severe in terms of their size, duration, intensity and impacts – is also on the rise. In Australia, the average wildfire frequency has doubled since 1980. In the forests of the western United States, wildfire severity, i.e. the degree of ecosystem impacts caused by a fire, increased eightfold between 1985 and 2017. The duration of the fire weather season has increased by 27% globally since 1979.

Climate change is exacerbating extreme wildfire risk. Higher atmospheric temperatures, variable precipitation patterns, the dryness of the landscape, and changing wind and lightning patterns have increased the risk of wildfires. Climate change is estimated to have doubled the total forest area burned in the western United States between 1984 and 2015. The extreme fire weather that facilitated the 2019-20 wildfires in Australia was estimated to be at least 30% more likely because of climate change. Moreover, emissions from extreme wildfires fuel climate change, which in turn further increases the frequency, size and severity of wildfire events, creating a feedback loop between climate change and extreme wildfires.

Unsustainable land-use practices and environmental degradation have also affected natural ecosystems' resilience to wildfires. Deforestation and the drainage of peatlands worsen drought conditions and increase landscape flammability, thereby contributing to the occurrence of extreme wildfires in countries such as Brazil and Indonesia. Certain agricultural and forestry practices also increase wildfire risk, as evidenced in 2017 in Portugal, where non-native eucalyptus provided highly flammable fuel. In most cases, human activity is also the main cause of wildfire ignition, responsible for nearly 70% of the total burned area globally.

Extreme wildfires cause significant social, environmental and economic disruptions. Their social costs go far beyond lives lost and include widespread health impacts. For example, at the global level, wildfire-induced air pollution is associated with 340 000 premature deaths annually. Extreme wildfires can also cause long-lasting and potentially irreversible ecosystem damage. Following the 2017 wildfires in Chile, nearly 40% of critically endangered habitats were significantly damaged, while the area where vegetation did not grow back after wildfires nearly doubled between 2000 and 2011 in some areas of the United States. The economic impacts of extreme wildfires are also mounting to unprecedented levels. The 2018 California Camp Fire caused around USD 19 billion in direct costs, while the 2019-20 wildfires in Australia caused USD 23 billion in direct costs.

How are countries strengthening their resilience to wildfire risk and what lessons can be drawn?

In response to the growing occurrence of extreme wildfires, affected countries have scaled up their emergency preparedness and response capacity. In the past 10-20 years, affected countries have increased resources to suppress wildfires up to fourfold. However, increasingly extreme wildfires have shown the limits of suppression in containing damage. Some extreme wildfires can take months to suppress, straining firefighting resources and limiting their effectiveness to contain wildfire impacts. The outbreak of several simultaneous fires increases the risk of fatalities. This underlines the importance for countries to strengthen their wildfire risk reduction measures *ex ante.*

Improve forest and vegetation management

Healthy ecosystems are more resilient and less prone to wildfire ignition and spread. Protecting and restoring degraded forests and peatlands has become a key element in many countries' wildfire risk prevention efforts. Costa Rica, Indonesia, South Africa and the United States are working to protect and restore forests and peatlands with a view to reducing wildfire risk. Further efforts are needed to curb illegal and unsustainable land use, including by scaling up monitoring and enforcement efforts.

Managing vegetation accumulation in the wildland-urban interface is also critical, as it reduces the amount of fuel available to burn. Fuel accumulation can be managed using prescribed fires and creating buffer zones and fuel breaks. Prescribed fires are commonly used in some countries such as Australia, Canada and the United States. Fuel breaks and buffer zones are increasingly mandated by government authorities but face barriers in terms of local implementation and enforcement capacities.

Adapt the built environment

Land-use planning and building codes and standards are key to protecting lives and economic assets and activities and play a key role in containing extreme wildfire risk and impacts. The significant social and economic impacts that resulted from recent extreme wildfires revealed gaps in the monitoring and enforcement of these measures, highlighting the need to strengthen compliance.

The vulnerability of infrastructure assets and networks to wildfires is a key determinant for the resilience of the whole society to wildfires. As a result, countries have started to develop regulations to require infrastructure owners and operators to abide by fire safety rules and develop contingency plans. However, wildfire regulations often lag behind and measures taken by infrastructure stakeholders remain voluntary.

Increase wildfire management capacity

Better wildfire risk assessments are critical to inform the changing needs for wildfire risk prevention. Up-to-date information on wildfire hazard, exposure and vulnerability and the integration of climate change impact models can help to better assess future wildfire risk while also effectively inform wildfire risk prevention and preparedness decisions.

A whole-of-government effort is critical to enhance wildfire risk prevention. Forest and land managers, critical infrastructure operators, spatial planning agencies, meteorological services, agriculture ministries, civil protection agencies, local governments, and private property owners all have a critical contribution to make in preventing wildfires. Co-ordination, collaboration and knowledge exchange across sectors and levels of government need to be strengthened. Initiatives to create central co-ordinating bodies, such as the Agency for the Integrated Management of Rural Fires in Portugal, can be effective governance arrangements.

Wildfire risk prevention also requires adequate funding. While strong recognition of the need to invest in wildfire risk prevention can be observed across countries, the increase in funding to date has mostly benefitted emergency preparedness and response capacities. Sufficient and stable public funding for wildfire prevention must be ensured, along with carefully considered crowding in of private wildfire prevention investments.

1 Overview: Key findings and recommendations

Recent extreme wildfire events have caused unprecedented damages and had impacts on human communities, economies and the environment. Climate change is a key driver behind the growing occurrence of extreme wildfires. Under projected warming, wildfire frequency and severity are set to increase, calling for a fundamental shift in wildfire management towards enhanced wildfire prevention. This chapter summarises the main findings of this report, outlining observed and projected patterns in extreme wildfire activity as well as the emerging policy solutions to address them. The recommendations aim to inform countries' policy progress towards building climate resilience to extreme wildfires.

1.1. An overview of wildfire risk and impacts across regions

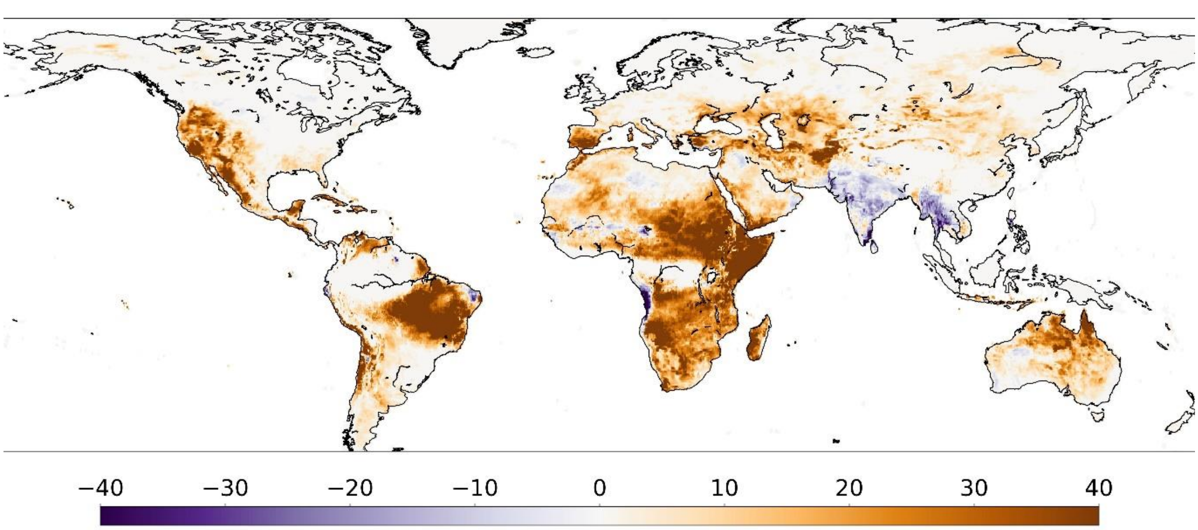
1.1.1. Extreme wildfires are a growing threat to humans, ecosystems and whole economies

Wildfire frequency, size and severity, as well as the duration of the fire season, are on the rise in many regions of the world. In Australia, average wildfire frequency almost doubled between 1980 and 2020, with an average annual increase in burned forest area of 350% between the early 1990s and 2018 (Canadell et al., 2021[1]). In the United States, wildfire severity (i.e. the degree of ecosystem impacts caused by a fire) increased eightfold between 1985 and 2017 across western forests (Parks and Abatzoglou, 2020[2]). The duration of the fire weather season, i.e. the annual period in which meteorological conditions are conducive to fire, grew by 27% globally between 1979 and 2019 (Jones et al., 2022[3]), with particularly large increases observed in southern Europe, western and central Asia, South America, western North America, Australia, and most of Africa (Jones et al., 2022[3]) (Figure 1.1).

The growing occurrence of extreme wildfires – i.e. wildfire events that are particularly severe in terms of their size, duration, intensity and impacts – can cause significant impacts on human lives and well-being, ecosystems and the climate system, as well as the economy. Extreme wildfire events have had particularly damaging impacts in recent years. The 2015 wildfires in Indonesia caused economic costs of about USD 16 billion, i.e. 2% of the national gross domestic product (GDP) (UNEP, 2022[4]). The 2018 Mati wildfires claimed over 100 lives in Greece (Kartsios et al., 2021[5]). The 2018 California Camp Fire produced an unprecedented USD 19 billion in economic damages, while in the following year, the 2019-20 wildfires in Australia burned 24-40 million hectares of land and caused an estimated USD 23 billion in economic damages (EM-DAT, 2023[6]; Royal Commission, 2020[7]).

Figure 1.1. Change in the duration of the fire weather season, 1979-2019

Change in the number of fire weather days



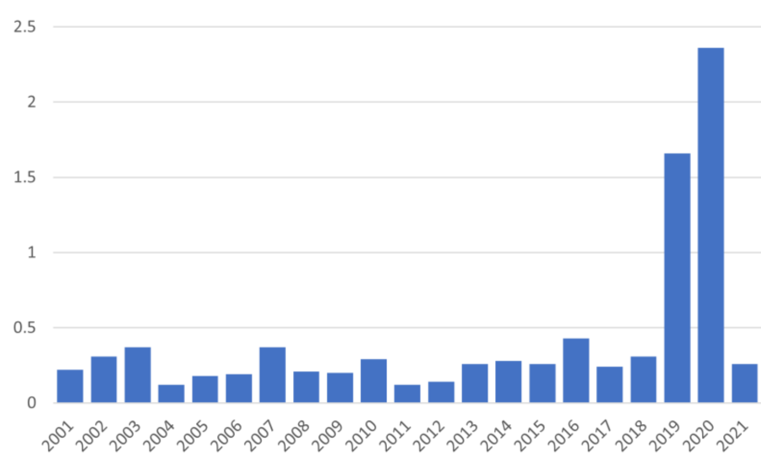
Notes: Cumulative change in the duration of the fire weather season between 1979 and 2019 based on data from Vitolo et al. (2020[8]) using the ERA5 dataset. Purple areas represent a decrease in the duration of the fire weather season, while brown areas represent an increase.
Source: Adapted from Jones et al. (2022[3]).

The human costs of wildfires go far beyond lives lost. Wildfires have long-term health impacts that can lead to respiratory and cardiovascular diseases and neurological disorders caused by wildfire-induced air pollution, as well as to psychological impacts (UNEP, 2022[4]). In the United States, smoke from wildfires is responsible for 25% of all harmful human exposure to $PM_{2.5}$ (fine particulate matter) and PM_{10} air pollution (USDA, 2022[9]). At the global level, the cardiovascular and respiratory impacts of wildfires are associated with 340 000 premature deaths every year (WWF, 2020[10]). 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[11]; Edwards et al., 2020[12]), which were associated with a direct health cost of USD 151 million (Glauber et al., 2016[13]). Wildfire-induced air pollution is projected to double by 2050 in several countries, including Canada, Mexico and the United States (Ford et al., 2018[14]). In addition, the traumatic experience of being caught in a wildfire, along with the displacement of populations and the loss of homes, livelihoods and personal belongings, can lead to major psychological trauma. For example, after the 2016 extreme Fort McMurray wildfire in Alberta, Canada, 60% of the evacuees experienced post-traumatic stress disorder (Belleville, Ouellet and Morin, 2019[15]).

Extreme wildfires can also have negative impacts on ecosystems. The 2019-20 wildfires in Australia caused the death or displacement of an estimated 3 billion animals, while almost 70 threatened species saw up to 50% of their habitat burned (Ward et al., 2020[16]; WWF, 2020[10]). Tree cover damage in the country was nine times higher in 2020 than in 2018 (WRI, 2021[17]) (Figure 1.2). Similarly, following the 2017 Chile wildfires, nearly 40% of critically endangered habitats suffered medium to high damage (van Hensbergen and Cedergren, 2020[18]). Freshwater ecosystems were also impacted during the 2019-20 Australia wildfires, with record fish mortality recorded in estuarine zones downstream of burned areas (Silva et al., 2020[19]). In some cases, increases in extreme wildfire events have also hampered ecosystem recovery after a wildfire. For example, in some areas of the United States, the area where pre-fire vegetation did not grow back to its initial state nearly doubled between 2000 and 2011 (Stevens-Rumann et al., 2018[20]). By affecting vegetation and soils, wildfires can also affect drinking water quality and increase water-related risks (UNEP, 2022[4]). For example, extreme wildfires can exacerbate drought and flood risk, as burned soils tend to absorb less water and increase run-off. While several studies have examined the short- and medium-term negative impacts of extreme wildfires on ecosystems, more systematic records of ecosystem damage and disruptions are needed to improve monitoring and inform wildfire risk reduction actions.

Figure 1.2. Trends of forest damage in Australia, 2001-21

Million hectares of forest area damaged



Note: 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[17]).

The economic costs of extreme wildfires are also significant. Between 2000 and 2017, wildfires are estimated to have caused EUR 3 billion of direct economic losses (e.g. lost and damaged assets, crops and livestock losses, etc.) every year in the European Union and USD 2.3 billion in the United States (Marsh & McLennan Companies, 2019[21]). Yet, direct costs only represent a share of higher costs to the economy and do not account for lost tax revenue, reduced property values, business interruptions, reduced productivity and recovery costs, among others. While these costs are often difficult to estimate, some studies suggest that total economic losses from wildfires in the United States could range from USD 63.5 billion to USD 285 billion every year (Thomas et al., 2017[22]). Between 2008 and 2012, the Amazon wildfires caused GDP losses of up to 1% in the state of Acre, Brazil (Campanharo et al., 2019[23]). While there is evidence for selected extreme wildfire events, there is no systematic record of past or future projected economic losses and damages from wildfires at the national or international level.

The wildland-urban interface (WUI), i.e. the area where the built environment and wildland vegetation meet, is where most socio-economic losses and damages from wildfires occur, as the exposure of people and assets is higher in these areas. In the western United States, the number of infrastructure assets destroyed by wildfires has increased by 246% over the past two decades (Higuera et al., 2023[24]). During the extreme 2018 Camp Fire in California, United States, over 18 800 buildings and infrastructure assets were destroyed (Karels, 2022[25]). In the United States, wildfires are estimated to cause a drop in property values of 10-20% on average up to 2 miles away from burned areas (WWF, 2020[10]). Certain economic sectors are particularly affected by wildfires. Between 2008 and 2018, wildfires were responsible for over USD 1 billion in losses in crop and livestock production globally (FAO, 2021[26]), while the 2017 wildfires in Canada alone resulted in the loss of a year's worth of timber production (Marsh & McLennan Companies, 2019[21]).

1.1.2. While wildfires are a natural part of ecosystem processes, extreme wildfires can cause abrupt and potentially irreversible disruptions

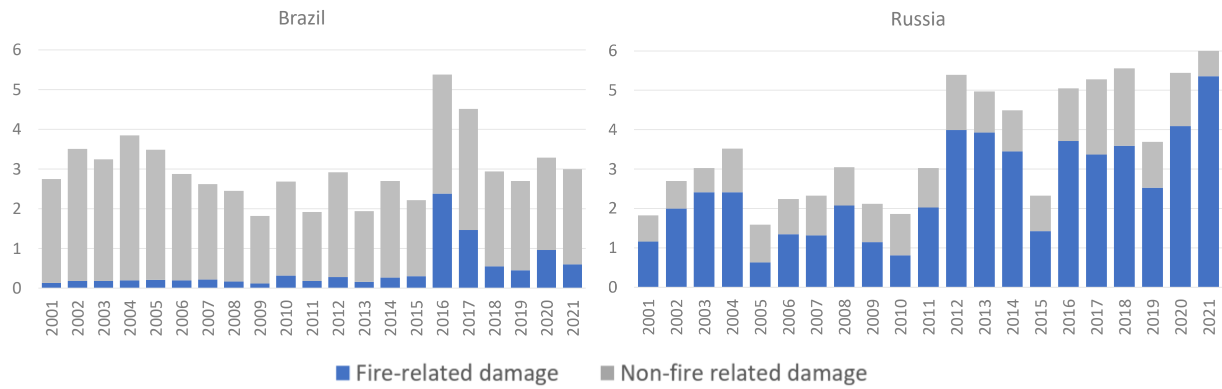
In many ecosystems, wildfires (i.e. unintended or uncontrolled fires that occur in wildland areas) are a natural component that provides important ecological functions. Species in these ecosystems may rely on regular fire activity to maintain their reproduction levels and growth (Hincks et al., 2013[27]). However, changing wildfire patterns pose growing challenges to the natural balance of ecosystems.

In ecosystems that are adapted to frequent or intense wildfires, such as boreal and Mediterranean forests, the growing occurrence of extreme wildfires has caused severe disruptions and hampered ecosystems' natural regeneration capacity (Turner et al., 2019[28]). In the Russian Federation (hereafter "Russia"), the extent of forestland affected by wildfires increased over fivefold between 2001 and 2021 (Figure 1.3).

Wildfires also increasingly occur where natural fire activity is rare, such as in tropical rainforests. In those areas, ecosystem resilience to fire is lower and the potential for irreversible damages is particularly high. For example, in 2016, wildfires affected more than 2.3 million hectares of forest area in Brazil (Figure 1.3) (WRI, 2021[29]). Intensive deforestation, combined with increased wildfire activity, has been associated with a large-scale, long-term tree cover loss in the Amazon region. This is pushing the Amazon rainforest towards a critical tipping point, which, if surpassed, might lead to abrupt and irreversible shifts in vegetation cover in the region, with impacts on global biodiversity and the global carbon cycles (Boulton, Lenton and Boers, 2022[30]; OECD, 2022[31]).

Figure 1.3. 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.
Source: Based on WRI (2021[29]) and WRI (2022[32]).

1.1.3. Important socio-economic drivers contribute to extreme wildfire occurrence and impacts

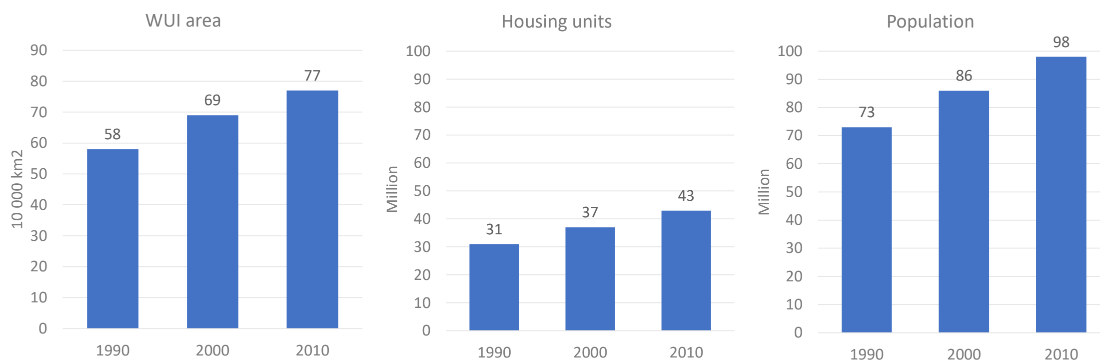
Human activity is the most common source of wildfire ignition and currently accounts for about 70% of the total land surface affected by fire globally (Veraverbeke et al., 2021[33]). The human ignition of wildfires can occur both accidentally (e.g. escaped campfires) or deliberately through arson. In France, Italy and Spain, over 95% of wildfires are caused by humans (WWF, 2019[34]). In the United States, it is estimated that over 80% of wildfires recorded between 2001 and 2009 were ignited by humans through accidents or arson (Hincks et al., 2013[27]). Utility failures, such as loose electricity cables or faulty power plants, were responsible for igniting 40% of the most destructive wildfires in California, including the devastating 2018 Camp Fire (LAO, 2021[35]). Similarly, downed power lines and arson were among the main ignition sources of the extreme 2009 Black Saturday wildfires in Australia (Parliament of Victoria, 2010[36]).

Human-induced ecosystem degradation is a key driver behind growing wildfire risk. The drainage of peatlands increases landscape flammability, as observed in Indonesia, where peatland degradation fuelled the extreme 2015 wildfires (UNEP, 2022[4]). Deforestation in Amazonia's and Indonesia's rainforests has also contributed to extreme wildfires, as permanent forest loss has worsened drought conditions and made ecosystems less resilient to wildfires (Nikonovas et al., 2020[37]; Pivello et al., 2021[38]). Certain agricultural and forestry practices, such as planting monocultures and non-native flammable species, also enhance wildfire risk, as shown during the wildfires in Chile in 2017, where non-native eucalyptus provided highly flammable fuel for wildfires over large areas (Barquín et al., 2022[39]).

Rural land abandonment and agricultural demise are other major socio-economic drivers of wildfire risk. Rural populations have played a key role in reducing fuel (i.e. vegetation) accumulation and continuity, including through agricultural practices (e.g. grazing and pruning trees in forests for firewood) and the creation of "mosaic" landscapes of agricultural crops that act as fuel breaks. With rural land abandonment, flammable vegetation encroaches and builds up. At the same time, rural land abandonment reduces the number of people available on the ground to detect and respond to wildfires early on (Moreira et al., 2020[40]). These trends are particularly marked in Mediterranean countries. For example, in Portugal, the 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 (World Bank, n.d.[41]).

The growing WUI has increased the exposure of people and assets to wildfires, eventually increasing the impacts and losses suffered by communities and economic activities. Between 1990 and 2010, the WUI area in the United States increased by 33% while the WUI population increased by 34% (Figure 1.4), contributing to the devastating wildfire impacts observed in recent years (Radeloff et al., 2018[42]). In Greece, the substantial WUI growth around the city of Athens is likely to have contributed to the devastating impacts of the Attica wildfires in 2018 (OECD, forthcoming[43]).

Figure 1.4. Wildland-urban interface (WUI) area, population and number of housing units in the United States, 1990-2010



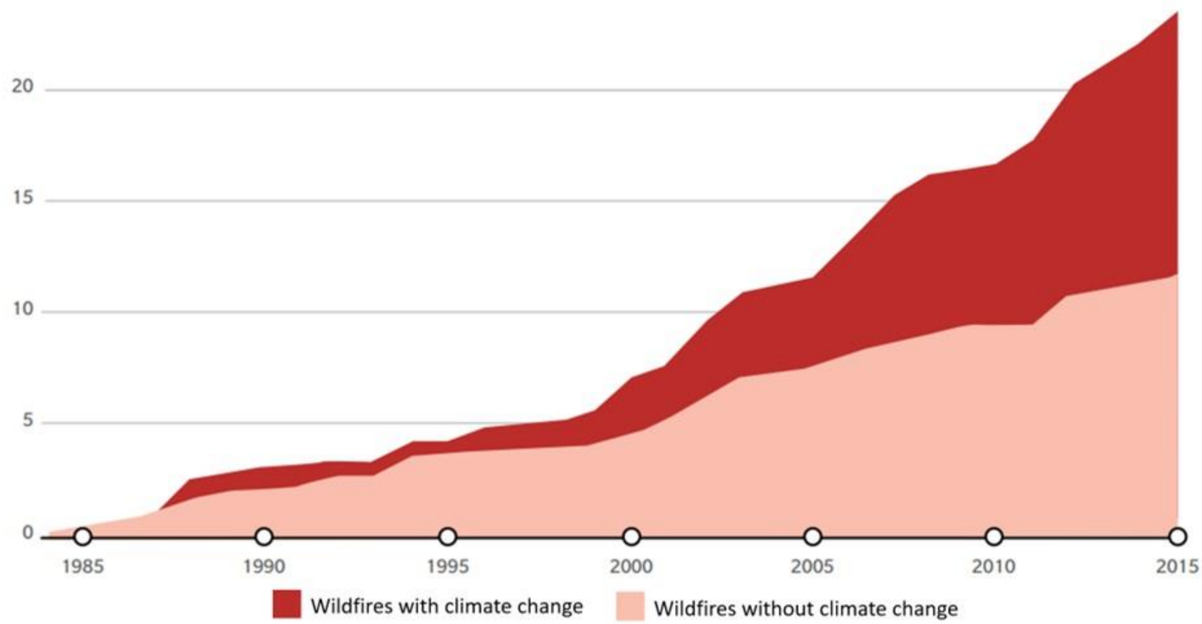
Notes: The WUI assessments were undertaken by Radeloff et al. (2018[42]) based on US Census data and the US Geologic Survey's NLCD.
Source: Based on Radeloff et al. (2018[42]).

There is mounting and conclusive evidence of the role of climate change in driving observed increases in wildfire extremes. Climate change influences the occurrence and patterns of wildfires by altering fire weather conditions. Higher atmospheric temperatures increase the occurrence of heatwaves and droughts, while earlier spring snowmelt can extend soil dryness for longer periods (Ellis et al., 2021[44]). In some regions, the reduced precipitation levels induced by climate change increase the dryness of the landscape, while climate change-induced alterations in wind and lightning patterns increase the likelihood of wildfire ignition and facilitate the spread of wildfires (UNEP, 2022[4]; IPCC, 2022[45]; Romps et al., 2014[46]). Besides, climate change also influences the characteristics and amount of fuel available to burn (Halofsky, Peterson and Harvey, 2020[47]). In some cases, increased precipitation during the vegetation-growing season can enhance the availability of fuel in the landscape, while the increased incidence of pests associated with higher temperatures and altered precipitation patterns can increase the amount of dead vegetation available to burn (Stephens et al., 2018[48]; Invasive Species Centre, 2022[49]).

The attributed climate change influence on observed wildfire extremes is stark. 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[50]) (Figure 1.5). The extreme fire weather that facilitated the 2019-20 wildfires in Australia 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[51]; Kirchmeier-Young et al., 2019[52]). A similar link has been established for the 2018 Camp Fire in the United States, where climate change is estimated to have doubled the likelihood of the extreme fire weather that facilitated the occurrence and spread of the blaze (Park Williams et al., 2019[53]; Goss et al., 2020[54]).

Figure 1.5. Cumulative forest area burned associated with climate change in the western United States, 1984-2015

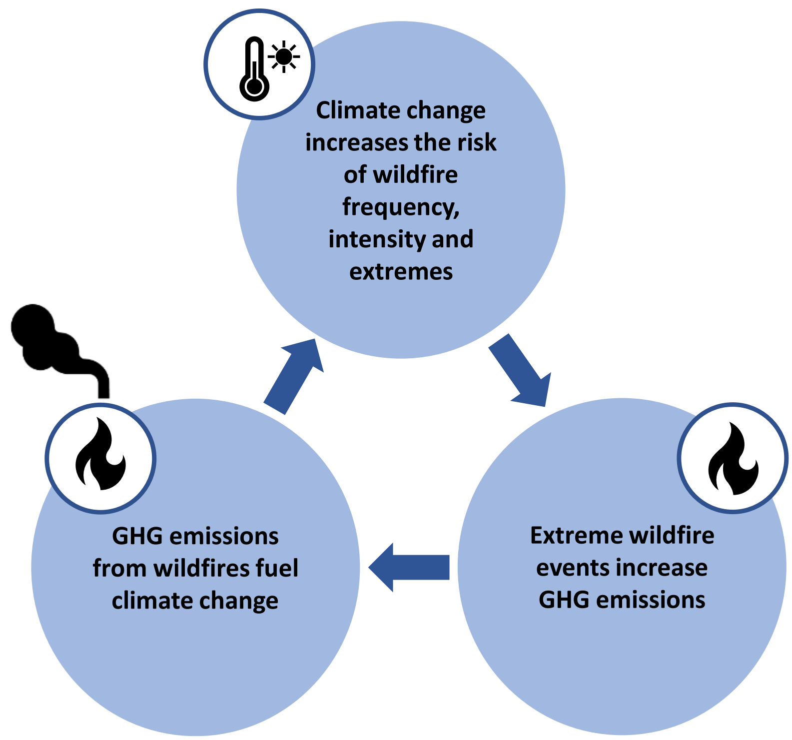
Million acres



Source: adapted from Marsh & McLennan Companies (2019[21]).

While human activities and climate change affect wildfires, wildfires, in turn, affect the climate system by releasing the carbon stored in vegetation and soil into the atmosphere (Figure 1.6). Under normal conditions, wildfires have a limited net influence on global carbon emissions, as wildfire emissions are mostly reabsorbed by regrowing vegetation in the aftermath of the fire (Jones et al., 2019[55]; Bowman et al., 2009[56]). However, with increasingly extreme wildfires, a net transfer of carbon dioxide (CO_2) from vegetation and the soil to the atmosphere has been observed (Friedlingstein et al., 2019[57]; Zheng et al., 2021[58]). For example, during the 2019-20 wildfires in Australia, CO_2 emissions were eight times higher than in the average wildfire season (van der Velde et al., 2021[59]). In 2020, the emissions from the California wildfires – which amounted to 127 million metric tonnes of CO_2 equivalent – were estimated to be twice as high as the total emission reductions achieved by the state as part of its climate change mitigation efforts between 2003 and 2019 (Jerrett, Jina and Marlier, 2022[60]). By burning vegetation and soil, extreme wildfires in forests and peatlands reduce land carbon storage capacity, further exacerbating this risk. Following the 1998 extreme wildfires in Russia, 2 million hectares of forestland lost their carbon storage capacity for at least a century (WWF, 2020[10]).

Figure 1.6. The feedback loop between climate change and extreme wildfires



Note: GHG: greenhouse gas.

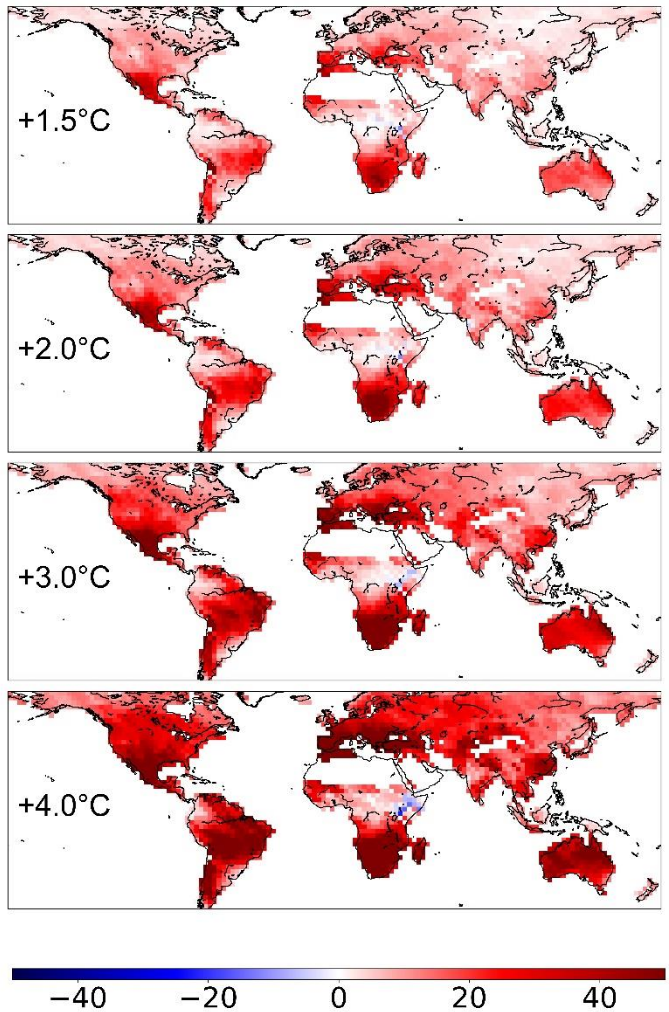
Source: Based on WRI (2022[32]).

1.1.4. Climate change is projected to further exacerbate future wildfire risk

Wildfire frequency and severity are set to rise in the future due to climate change (UNEP, 2022[61]). Under a 2°C warming scenario, many regions are projected to experience a large increase in wildfire frequency. Rising temperatures and drought conditions, coupled with changing precipitation and wind patterns, are also likely to extend the duration of the fire season (i.e. the period when weather conditions are conducive to the occurrence of wildfires) in most regions of the world, extending it by over 40 days per year in parts of the world under a high-warming scenario (Xu et al., 2020[62]; Bowman et al., 2020[63]; Jones et al., 2022[64]) (Figure 1.7). As a consequence, wildfire impacts are also likely to grow. Globally, area burned is projected to increase by 19% by 2050 (compared to 2000), under a moderate-emission scenario (RCP 4.5) (Zou et al., 2020[65]), while under a 4ºC warming scenario, wildfire frequency is projected to increase by 30% by the end of the century (IPCC, 2022[45]). By 2100, the yearly burned area in Greece's forests is projected to increase by up to 20% (compared to 2010 levels), leading to an annual direct cost of EUR 40 million to EUR 80 million by 2100 (Bank of Greece, 2011[66]). In Portugal, wildfire-induced losses in the tourism sector are projected to reach up to EUR 62 million annually by 2030, while by 2050, such losses are expected to at least quadruple (Otrachshenko and Nunes, 2022[67]).

Figure 1.7. 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[64]) based on Jones et al. (2022[3]).

1.2. Adapting wildfire management to growing wildfire risk: State of play and policy recommendations

1.2.1. Changing wildfire risk calls for adapting wildfire management policies and practices

Countries need to adapt their wildfire management systems to limit future wildfire-induced losses and damages. Large and more frequent and intense wildfires will require significant suppression and emergency preparedness efforts, including fire monitoring and early warning systems. More importantly, wildfires need to be tackled at their source by scaling up preventative action. Fuel loads need to be better monitored and managed; ecosystems need to be protected from degradation; planted forest species need to be adapted to changing fire conditions; and wildfire risk assessments need to be better integrated into land-use decisions. Co-ordinated action and a strong enabling environment are required to enable changes to existing practices.

1.2.2. Countries have strengthened their emergency preparedness and response capacity

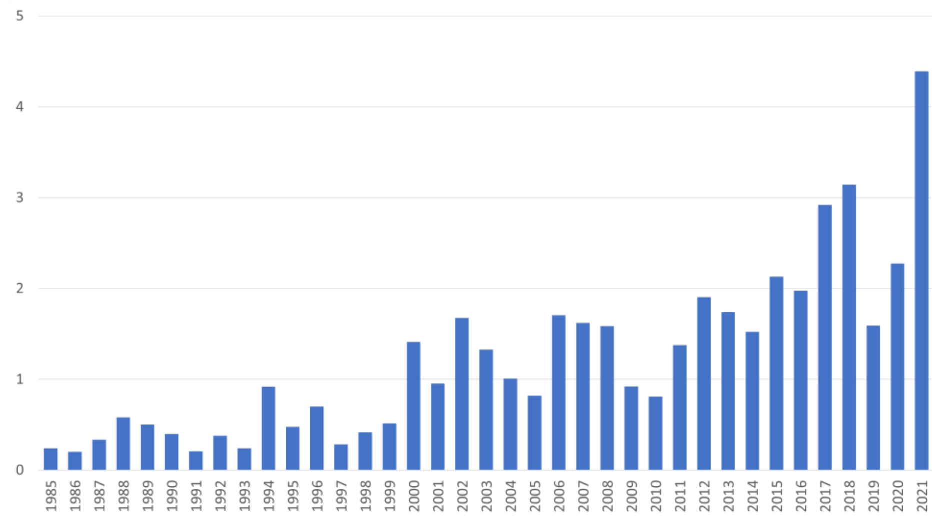
In reaction to extreme wildfires, some countries have significantly scaled up their emergency preparedness and response capacities, with a particular focus on strengthening wildfire suppression. Between 1998 and 2008, Greece doubled the public funding allocated for wildfire suppression, significantly scaling up aerial firefighting capacity (Xanthopoulos, 2008[68]), while the United States significantly increased federal funding for wildfire suppression (Figure 1.8), from an average USD 425 million per year in 1985-99 to USD 1.6 billion per year in 2000-19 (Roman, Verzoni and Sutherland, 2020[69]). Some countries have also enhanced cross-border co-operation mechanisms to support each other during emergency periods. For example, the European Union (EU)'s Civil Protection Mechanism, which co-ordinates disaster response across EU member and neighbouring countries, was further strengthened through the creation of rescEU operation, with a EUR 170 million funding envelope to enhance firefighting capacity across Europe (European Commission, 2022[70]). Several bilateral mutual support agreements also exist, e.g. between Canada and the United States (OECD, forthcoming[71]).

To better detect large wildfires, countries have also enhanced their wildfire risk monitoring capacities by strengthening their weather and fire monitoring systems. The European Forest Fire Information System (EFFIS) and EU Copernicus programme provide near-real time fire activity information (EFFIS, n.d.[72]; European Commission, n.d.[73]). The North American Space Agency (NASA) tracks soil moisture, provides vegetation maps, and monitors fire ignitions, active fires and post-fire recovery (NASA, n.d.[74]). These efforts are critical to detect potentially extreme fires early on and allocate resources accordingly.

Despite these significant efforts, increasing wildfire size, frequency and severity have highlighted the limits of emergency response measures (Xanthopoulos, 2008[68]; Parisien et al., 2020[75]; European Commission, 2021[76]) and the need to reduce the risk of extreme wildfires at the source (Ministry of the Environment and Energy, Greece, 2018[77]; Myers, 2006[78]). Extreme wildfire seasons have strained emergency response resources, limiting their ability to contain impacts. This challenge was observed, for example, during the extreme 2009 Black Saturday wildfires in Australia, which took over one month of firefighting efforts to be suppressed (Caohuu et al., 2015[79]). Similarly, during the 2017 wildfires in the Iberian Peninsula, the rate of fire spread exceeded the available firefighting capacity by three to nine times (WWF, 2020[10]). During the 2018 extreme wildfire season in Greece, the outbreak of multiple wildfires at the same time created a bottleneck in the deployment of firefighting resources, contributing to an unprecedented wildfire death toll in Mati, where over 100 people lost their lives (Xanthopoulos and Athanasiou, 2019[80]). In Alberta, British Columbia, and Ontario, Canada, wildfire suppression spending is projected to have to double by the 2071-2100 period to keep the current levels of fire response success (Hope et al., 2016[81]).

Figure 1.8. Increase in wildfire suppression costs in the United States, 1985-2021

Billion USD



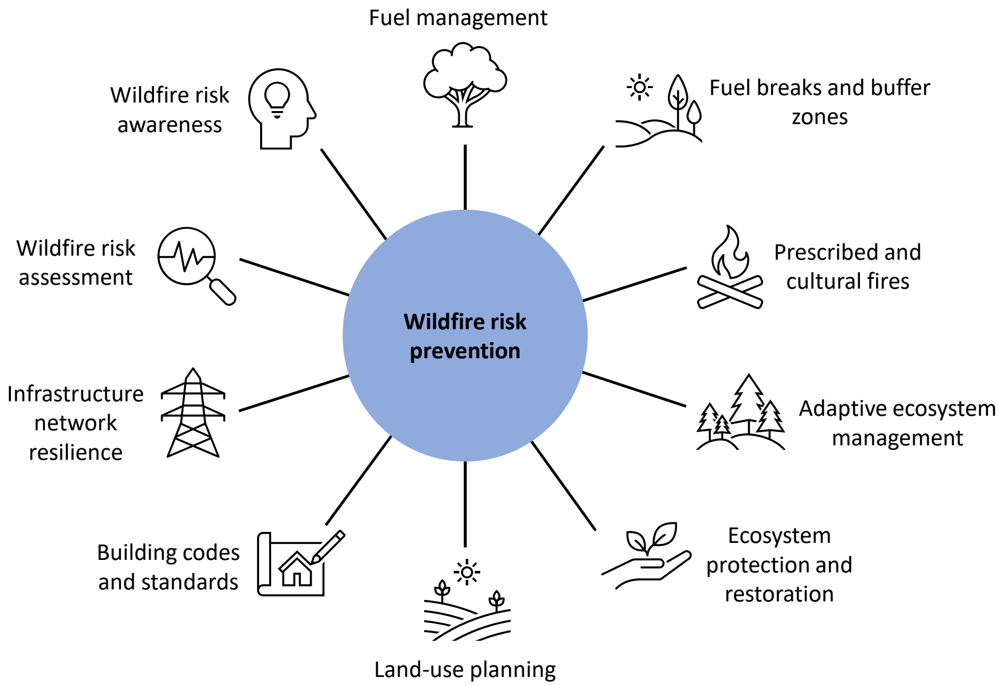
Note: The chart represents federal costs, including those incurred by the US Fire Service and the Department of the Interior's agencies.
Source: Based on data from the National Interagency Fire Center (n.d.[82]).

1.2.3. Reducing the risk of extreme wildfires relies on scaling up risk prevention measures

In the context of growing extreme wildfire risk, scaling up climate change adaptation measures as part of wildfire risk reduction efforts is critical. Only preventative action can effectively reduce wildfire hazard and exposure and vulnerability to wildfire impacts, while of course climate mitigation actions remain critical to addressing the climate driver at its source.

Wildfire prevention can take several forms (Figure 1.9), including organisational as well as structural measures. Organisational measures include wildfire hazard and risk assessment, awareness raising, as well as legislative and regulatory measures. Structural or "physical" measures include ecosystem-based interventions such as ecosystem protection, restoration and adaptive management, as well as fuel management interventions, including the creation of fuel breaks and buffer zones and the use of prescribed fires. Appropriate institutional, policy and financial arrangements are necessary to enable investments in risk prevention measures.

Figure 1.9. Reducing the risk of extreme wildfires through prevention measures



1.2.4. The protection, restoration and adaptative management of ecosystems reduce the occurrence and impacts of wildfires

Healthy ecosystems are more resilient and less prone to negative wildfire impacts. Climate change, combined with ecosystem degradation, has led to more fire-prone conditions in many regions. Following extreme wildfire events, the protection and restoration of degraded forests and peatlands has become a key element in many countries' wildfire risk prevention efforts. Forest restoration efforts – which can entail interventions such as reforestation, tree diversity restoration, and the control of invasive and underbrush species (i.e. species growing underneath the tree canopy) (Tobin-de la Puente and Mitchell, 2021[83]) – are at the centre of wildfire risk prevention efforts in Costa Rica, Gambia and South Africa (UNEP, 2021[84]; Republic of South Africa, 2022[85]). The United States has recently issued an executive order to protect old-grown forests with a view to reducing wildfire risk (The White House, 2022[86]).

Similarly, in the aftermath of the 2015 extreme wildfires, Indonesia extended the moratorium on issuing new permits for the development on primary forests and peatlands (Wijaya et al., 2016[87]) and established an agency dedicated to peatland restoration (Ward et al., 2021[88]; Wijaya et al., 2016[87]). Yet, further efforts are needed to effectively protect and restore wildland ecosystems from illegal activity and unsustainable land-use changes, as well as to scale up monitoring and enforcement efforts. In some cases, unclear or unknown forest ownership also limits the effectiveness of these measures (The Nature Conservancy and Aspen Institute, 2023[89]).

In light of climate change, some countries have also scaled up their efforts to ensure the adaptive management of forests to reduce landscape flammability. Managing forests in an adaptive manner can include, for example, planting fire-resilient species and excluding particularly fire-prone species in high-risk areas to adapt vegetation cover to growing wildfire and drought risk (Fitzgerald and Bennett, 2013[90]). These interventions are particularly important given the increasing prevalence of highly flammable non-native species in some countries. For example, in mainland Portugal, the extent of eucalyptus forests – which are highly flammable – grew by 62% between 1990 and 2017 (APA, 2020[91]). To address this challenge, the country developed a financial scheme promoting the plantation of native species on private lands to reduce landscape flammability (OECD, forthcoming[92]). However, scaling up and monitoring such adaptive forest management is key, especially in the context of climate change.

1.2.5. There is growing recognition of the importance of fuel management

Managing fuel accumulation in the wildland-urban interface is critical for reducing wildfire risk and impacts, as it reduces the amount of vegetation available to burn, especially in the vicinity of exposed settlements or assets. Fuel accumulation is usually managed through the use of prescribed fires (i.e. controlled fires to reduce fuel accumulation) and mechanical fuel removal or grazing to create buffer zones (i.e. strips of non-flammable land near settlements) and fuel breaks (i.e. patches of non-flammable land that reduce fuel continuity).

Prescribed fires are a relatively common tool to manage fuel accumulation and wildfire risk. While some countries, such as Australia and the United States, largely rely on prescribed fires to reduce fuel accumulation (Burrows and McCaw, 2013[93]; Melvin, 2021[94]), their use is limited in several European countries. France and Portugal have only recently set up specific legal frameworks to regulate and enable the safe use of fire (Montiel and Kraus, 2010[95]). The traditional use of fire in agricultural and land-use practices has led Australia, the United States and the Bolivarian Republic of Venezuela to engage with indigenous and local communities to integrate the active use of fire in wildfire prevention plans (Pardo Ibarra, 2020[96]; OECD, 2021[97]). In Australia, the enhanced use of cultural fires, i.e. fires ignited by indigenous groups and local communities to manage the land, was associated with a 50% reduction in area burned between 2000-06 and 2013-19 (OECD, forthcoming[98]). Despite the good practices described above, the high-risk perception associated with prescribed and cultural fires, together with limited awareness of their benefits, hampers their effective use in many countries (Müller, Vilà-Vilardell and Vacik, 2020[99]; Montiel and Kraus, 2010[95]).

Fuel breaks and buffer zones are more commonly used fire risk prevention measures. In Australia and Portugal, extended fuel breaks systems that strategically alternate different land cover types have effectively reduced landscape flammability (OECD, forthcoming[98]; forthcoming[92]), while after the extreme 2018 Camp Fire, the municipality of Paradise (California) bought some of the private lands most affected by the blaze to turn them into non-flammable fuel breaks (Brasuell, 2021[100]). Following particularly extreme wildfire events, both Greece and Portugal also mandated the creation and maintenance of buffer strips in high-risk areas. In Portugal, these are mandatory for both new and existing buildings in WUI areas; in Greece, tenants and owners in high-risk areas are required to remove excess vegetation and other flammable materials from the perimeter surrounding their assets before the start of the wildfire season (OECD, forthcoming[92]; forthcoming[43]). Yet, local governments face limited monitoring and enforcement capacities, thus reducing the full potential of fuel break measures (Moreira et al., 2020[40]; OECD, forthcoming[92]).

Acknowledging the importance of private stakeholder engagement in fuel management, many countries have also increased awareness-raising efforts to promote a better understanding of existing risk levels and have developed incentives to encourage active land management in private lands. In the United States, tax credits and deductions are available for farmers and landowners to encourage active fuel management on private lands (Kunreuther and St. Peter, 2020[101]). In Mediterranean countries such as France, Israel, Portugal and Spain, incentives to shepherds to encourage grazing activities on fuel-rich land have proven a winning strategy to contain fuel accumulation (Komac et al., 2020[102]). Portugal's Condomínio de Aldeia programme promotes active land management through community engagement (OECD, forthcoming[92]). However, low monitoring and enforcement, together with the lack of official land registries and unclear forest ownership, can limit the effectiveness of these measures (The Nature Conservancy and Aspen Institute, 2023[89]). This is the case, for example, in Portugal, where over 20% of forestlands have no or unknown owner and only 46% of forest areas are covered by the land registry. To address these issues, Portugal has recently released a new law which enables the state to carry out fuel management activities in areas of unknown ownership or where the owner fails to carry out the requested management efforts (OECD, forthcoming[92]).

1.2.6. Land-use planning and building regulations are critical to protecting lives, livelihoods and socio-economic assets

Land-use planning is critical to limit the exposure of human lives and assets to wildfire risk. Most notably, land-use zoning can limit urban sprawl in the wildland-urban interface (see Section 1.1.3). To inform this, wildfire hazard models need to be integrated into land-use planning processes. In recent years, countries have used land-use zoning to reduce wildfire exposure. For example, in France and Portugal, the construction of new buildings is generally forbidden in zones characterised as "high" or "very high" wildfire risk (OECD, forthcoming[92]; Presidency of the Council of Ministers, Portugal, 2021[103]; Kocher et al., 2017[104]). In France, housing development in "moderate" wildfire risk areas is allowed when specific risk reduction measures are adopted, such as the use of non-flammable building materials (Kocher et al., 2017[104]). On the other hand, in Greece, unclear zoning and high demand for development in the WUI, combined with an outdated hazard map, has contributed to housing expansion in fire-prone areas (Triantis, 2022[105]; Blandford, 2019[106]). During the Mati wildfire in 2018, the high number of assets that did not have a building permit contributed to the severe wildfire impacts, resulting in a building destruction rate of 80% (Hellenic Republic, 2021[107]; Blandford, 2019[106]; OECD, forthcoming[43]).

Building codes and standards also play a key role in minimising the impacts of wildfires once these occur. Buildings constructed with non-flammable materials and incorporating fire protections such as metal screens and spark arresters can reduce wildfire impacts fivefold compared to highly flammable structures (Czajkowski et al., 2020[108]). Countries have developed stricter standards for building design and maintenance in high-risk areas. For example, Greece and Portugal mandate the use of non-flammable materials and structural protection measures for new buildings and set out requirements on retrofitting existing ones in high-risk areas (OECD, forthcoming[92]; forthcoming[43]; Hellenic Republic, 2021[107]). In an effort to strengthen building code compliance, some communities in the United States have started to issue fines (Roman, 2018[109]).

1.2.7. Infrastructure design, operation and management contribute to wildfire resilience

As wildfire risk grows, strengthening infrastructure resilience is critical. This includes effectively planning and managing infrastructure to reduce the risk of wildfire ignition, as well as designing infrastructure assets and networks that are themselves resilient to wildfire risk by ensuring the continuity of their services and operations even in the occurrence of a wildfire event. The level to which critical infrastructure systems are resilient to wildfire risk contributes to society's resilience as a whole (IPCC, 2022[110]). Countries have developed regulations to require infrastructure operators to abide by fire safety rules and develop contingency plans. For example, Canada requires its two largest train companies to reduce train speed during high wildfire risk periods, as well as to remove flammable materials from the tracks (Scherer, 2021[111]). Following the extreme 2009 Black Saturday wildfires, the state of Victoria, Australia, established an AUD 750 million Powerline Bushfire Safety Program, which – by upgrading the electricity distribution network and regulating infrastructure management – was successful in reducing wildfire risk from powerline ignition (OECD, forthcoming[98]; Victoria State Government, 2022[112]). In Portugal, the Climate Change Adaptation Action Plan sets the ambition to have 50% of its transport infrastructure companies develop an adaptation or contingency plan for extreme events by 2030 (Government of Portugal, 2019[113]). Yet, in many cases, government regulations lag behind in this field, with wildfire prevention measures often being implemented by infrastructure operators on a voluntary basis.

1.2.8. Better wildfire risk assessments are needed to inform the changing needs for wildfire risk prevention

Information on wildfire hazard and wildfire risk is the basis for all wildfire risk prevention and preparedness decisions. Countries are increasingly aware of changing wildfire patterns and the need to better account for the links between climate change and extreme wildfire risk. An increasing amount of geospatial data has become available, allowing to better understand, model and map wildfire hazard, drivers and behaviour over time. Based on these data, many countries have developed hazard maps that are used to inform wildfire policy interventions throughout the territory. For example, Portugal and the United States have national wildfire hazard maps that classify the territory by hazard level (USDA, n.a.[114]; DGT, n.a.[115]). In Portugal, each municipality is also required to have a wildfire hazard map, which must be updated every ten years (OECD, forthcoming[92]; forthcoming[71]). However, hazard assessment alone is not sufficient to provide a comprehensive assessment of wildfire risk. As exposure and vulnerability are key drivers of risk, wildfire hazard assessments need to be integrated with spatial information on the exposure and vulnerability of human and ecological assets and systems. Yet, in most cases, integrating socio-economic information into wildfire risk assessments remains a challenge. While the United States has started to develop wildfire risk maps, which integrate hazard data with information on human and asset exposure and vulnerability (OECD, forthcoming[71]; Jacome Felix Oom et al., 2022[116]), these are not yet developed systematically by most countries. Persisting data gaps limit the availability of hazard and risk maps at different spatial scales and challenge their regular update. Limitations in wildfire models' predictive capacity limit the accuracy of existing projections. Besides, even where projections on future wildfire activity do exist, they are often not integrated into risk assessment and planning processes. Overall, countries struggle to integrate and keep abreast of growing scientific knowledge on the complex links between climate change and extreme wildfire hazard.

1.2.9. A cross-governmental effort is needed to reduce wildfire risk

The drivers of wildfire risk, as well as some of the key tools available to manage those risks, link to the roles and responsibilities of several stakeholders. For this reason, wildfire risk prevention needs to be integrated into the work of many sectors and all levels of government. Forest and land managers, critical infrastructure operators, spatial planning agencies, meteorological services, agriculture ministries, civil protection agencies, local governments, and private property owners all have a critical contribution to make in preventing wildfires. Countries are seeking to leverage this whole-of-government approach in different ways. Australia, Portugal and the United States have developed national wildfire management strategies that provide an overarching policy framework guiding the work of all relevant agencies. For example, Portugal's National Plan for Integrated Rural Fire Management establishes national policy objectives on wildfire management (OECD, forthcoming[92]). The first mid-term review in 2025 will show how well this ambitious plan has helped foster prevention across government agencies (OECD, forthcoming[92]).

To further reinforce the whole-of-government effort for preventing wildfires, some countries have also created dedicated co-ordinating agencies. In response to the 2017 wildfires, Portugal established the Agency for the Integrated Management of Rural Fires (AGIF), a cross-governmental body under the authority of the Prime Minister that promotes collaboration, fosters knowledge exchange and co-ordinates actions by relevant agencies and stakeholders through cross-governmental committees (OECD, forthcoming[92]). In only a few years, AGIF succeeded in bringing wildfire prevention to the centre of wildfire management efforts in the country. In 2022, Greece created a joint ministry for civil protection and climate change adaptation in an effort to strengthen prevention investments for climate-related risks, including wildfires (OECD, forthcoming[43]).

The degree to which wildfire risk reduction efforts are integrated across all relevant government agencies can be seen in the mainstreaming of prevention considerations into sectoral policies. For example, in Greece, the National Forest Strategy sets out objectives for wildfire prevention by identifying priority areas for action, developing forest maps, informing wildfire management interventions and preparing forest fire prevention plans (OECD, forthcoming[43]; Ministry of the Environment and Energy, Greece, 2018[77]). Similarly, in Portugal, the National Forest Strategy and its subordinate regional forest management programmes encourage the active management of forested lands, while the National Programme for Spatial Planning Policy identifies the rural areas most exposed to wildfire risk and outlines key adaptation actions (OECD, forthcoming[92]; APA, 2020[91]; Council of Ministers, Portugal, 2015[117]; Government of Portugal, 2021[118]).

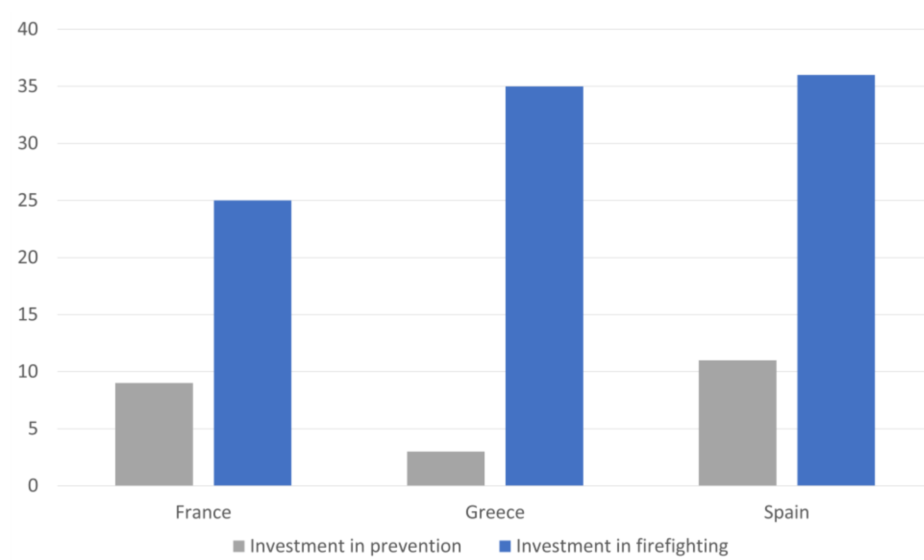
Despite these promising efforts, wildfire management remains fragmented in many countries. Evidence from Greece and Portugal shows that the limited collaboration and co-ordination across governments, key agencies and sectors has limited the effectiveness of wildfire management (OECD, forthcoming[43]; forthcoming[92]). For example, until recent improvements, collaboration has been low between agencies responsible for wildfire prevention and suppression actors in Greece (GFMC, 2019[119]). The investigations carried out after the 2017 extreme wildfires in Portugal also found that the unclear distribution of roles and responsibilities has led to institutional overlaps or gaps, contributing to the high wildfire impacts (Council of Ministers, Portugal, 2020[120]; OECD, forthcoming[92]). Overall, the effective integration of wildfire prevention into sectoral policies remains the exception rather than the norm.

1.2.10. Wildfire risk prevention needs appropriate funding

While strong recognition of the need to invest in wildfire risk prevention can be observed across countries, the increase of available funding to date has mostly benefitted emergency preparedness and response capacities. Wildfire suppression spending in many wildfire-prone countries is still up to six times higher than the recorded risk prevention spending (Figure 1.10). In Greece, the funding allocated to the Forest Service – the main entity responsible for wildfire prevention – shrank by nearly 30% between 2010 and 2017, from EUR 116 million to EUR 83 million (GFMC, 2019[121]; OECD, forthcoming[43]). In many countries, funds initially earmarked for wildfire prevention get diverted to fund emergency response, further exacerbating prevention funding gaps (North et al., 2015[122]).

Figure 1.10. Public investments in prevention and suppression in France, Greece and Spain

EUR per forest hectare

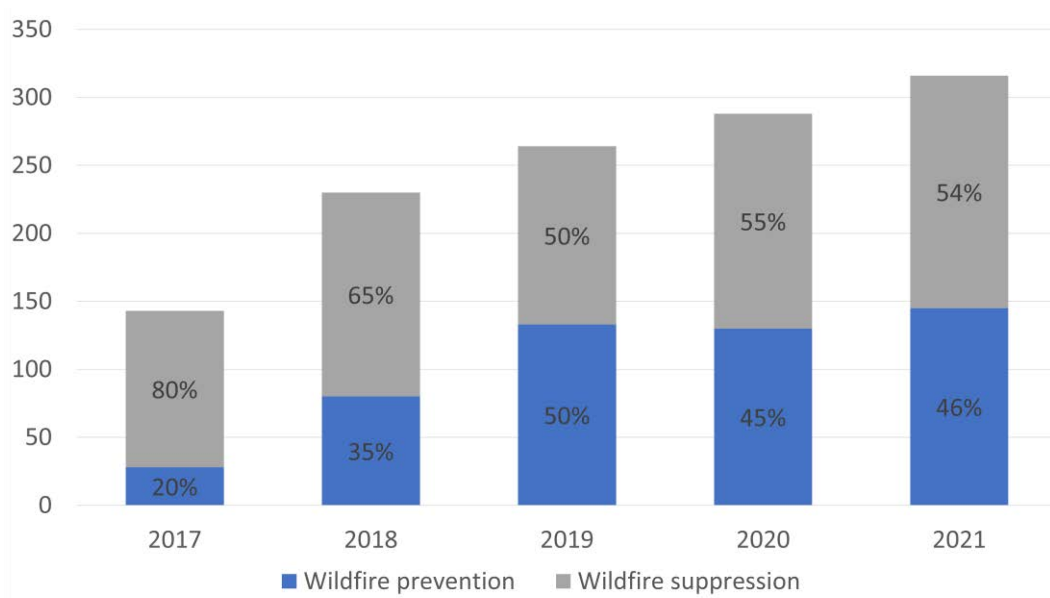


Notes: Information on Spain is based on data from the Spanish Official School of Forestry Engineers and refers to the period 2008-17. It includes state and regional investment, as regional governments share competences in forest management. Information on France is based on data from the National Institute of Geographic and Forest Information and refers to the period 2009-18. Information on Greece is based on WWF estimations.
Source: Based on WWF (2019[34]).

In some countries, extreme wildfires in recent years have triggered a shift in resource allocation. In response to the extreme 2017 wildfires, Portugal significantly boosted the public budget available for wildfire prevention (AGIF, 2021[123]), bringing prevention and suppression funding to near parity (Figure 1.11). While in 2017 only 20% of wildfire management funding was allocated to prevention, by 2021 wildfire prevention received 46% of all public wildfire funds, reaching EUR 145 million (OECD, forthcoming[92]; AGIF, 2021[123]). Funding for wildfire prevention also increased in Greece in 2022, thanks to support from the EU Recovery and Resilience Facility, in addition to national funding efforts. As a result, EUR 72 million were allocated for the AntiNero wildfire prevention programme (Ministry of the Environment and Energy, Greece, 2022[124]; OECD, forthcoming[43]).

Figure 1.11. The shifting focus from suppression to prevention in national public funding in Portugal, 2017-21

Million EUR



Source: Based on AGIF (2021[123]).

Insurance coverage for wildfire risk can also play a key role in scaling up wildfire prevention by identifying areas at risk and incentivising private investments in risk reduction measures. Insurance premiums can be made to reflect the level of exposure and vulnerability of insured assets. For example, lower insurance premiums can be offered to policy holders whose assets are in line with wildfire building standards. In the United States, some insurance companies give a 5% discount on insurance premiums to homeowners that undertake certain wildfire prevention measures (Galbraith, 2017[125]). In California, the "Safer from Wildfires" programme legally mandates insurance providers to reward wildfire prevention efforts undertaken by insured individuals by reflecting these in risk scores and giving corresponding discounts on insurance premiums (California Department of Insurance, n.d.[126]). In the absence of insurance coverage for wildfire risk, governments often step in to compensate for privately incurred losses and damages. Catastrophe risk insurance programmes, such as France's CatNat system, can be a way to keep insurance premiums affordable while backing up insurance providers through a state guarantee in case of an extreme event (OECD/The World Bank, 2019[127]).

Yet, despite some efforts, countries struggle to secure sufficient insurance availability, affordability and coverage in risk-prone areas. In high-risk areas, access to insurance is rendered ever more difficult by the growing occurrence of extreme wildfires. For example, after the 2018 wildfires in California, insurance premiums rose by up to 500% in some areas. Insurance providers also refused to renew their coverage after the devastating Camp Fire, leaving 340 000 policy holders uninsured (Moss and Burkett, 2020[128]). Even when insurance is available, uptake rates remain low. For example, only 9% of all wildfire losses in Greece were covered by insurance between 1990 and 2019 (OECD, 2021[129]).

Box 1.1. Recommendations: Adapting to a changing climate in the management of wildfires

Strengthen ecosystem protection and adaptive management for wildfire prevention

- Protect wildland ecosystems from degradation, illegal activity and land-use change through strict regulations, monitoring and enforcement.
- Restore degraded ecosystems to reduce their proneness to wildfire risk and secure the continued provision of their ecosystem services.
- Manage forests to adapt their structure and composition to changing wildfire risk in line with local needs and conditions.

Scale up fuel management efforts to reduce fuel accumulation and continuity

- Mandate the use and maintenance of buffer zones to protect assets in wildlife-urban interface (WUI) areas and ensure enforcement through regular monitoring and penalties for non-compliance.
- Develop fuel break systems and landscape mosaic areas to reduce landscape flammability, most notably near WUI areas.
- Enable the active use of fire for fuel management, agricultural and other purposes, establishing safe conditions and monitoring systems for its use.

Strengthen land-use planning and building regulations for wildfire prevention

- Regulate development in fire-prone areas via zoning regulations, restricting development in high-risk areas.
- Develop building codes and standards that mandate fireproof building design for new and existing buildings.
- Regulate infrastructure planning, design and operations to reduce wildfire risk, including by promoting resilient design, regular monitoring and maintenance, or network reconfiguration where needed.
- Ensure compliance with land-use planning and building regulations via awareness raising, economic incentives, and stricter monitoring and enforcement.

Harness knowledge for better wildfire management and improve wildfire risk assessments

- Update information on wildfire hazard, exposure and vulnerability regularly.
- Integrate climate models into wildfire hazard assessments.
- Develop wildfire projections that integrate information on future climate and socio-economic changes under different scenarios.
- Integrate policy-relevant knowledge on wildfires, including lessons learnt from extreme fires, into all relevant policies and practices.

Strengthen the policy and institutional framework

- Promote a whole-of-government approach to wildfire management; national, integrated wildfire risk management strategies and central co-ordinating agencies can be useful implementation vehicles.
- Integrate wildfire risk prevention across all relevant sectors, ensuring policy coherence and alignment, especially in land use, infrastructure development and forest management.
- Ensure the engagement of all relevant government agencies as well as the participation of relevant non-governmental stakeholders.
- Strengthen co-ordination, collaboration and knowledge exchange across sectors and levels of government through cross-governmental agencies or cross-sectoral platforms.

Scale up funding and risk transfer instruments for wildfire risk reduction

- Ensure sufficient and stable public funding for wildfire prevention and encourage private investment in wildfire risk reduction through incentives and subsidies.
- Encourage the provision and uptake of insurance covering wildfire risk and ensure its availability and affordability for assets and activities in high-risk areas that cannot be relocated.
- Develop compensation mechanisms that do not discourage *ex ante* investments in risk prevention, self-protection and insurance.

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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.

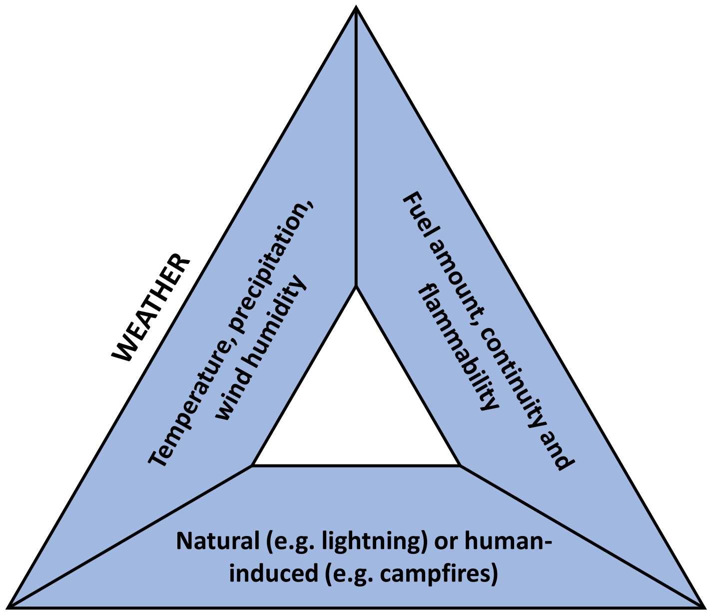
Wildfires can be further characterised by the vegetation they burn:

- *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]).

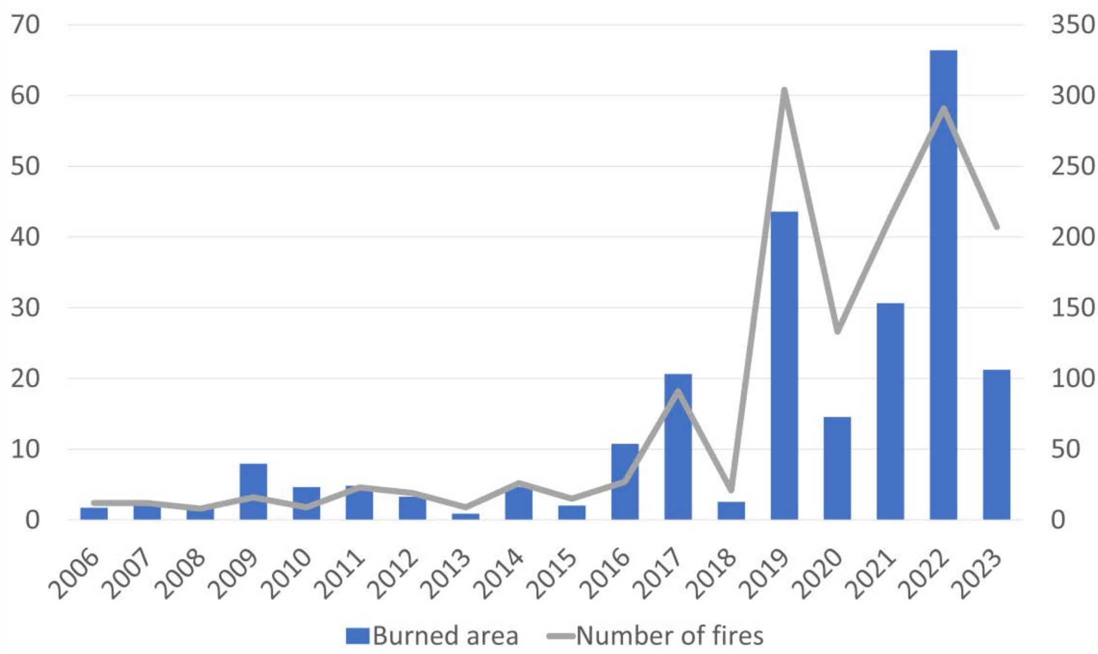
2.3. Observed wildfire trends

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

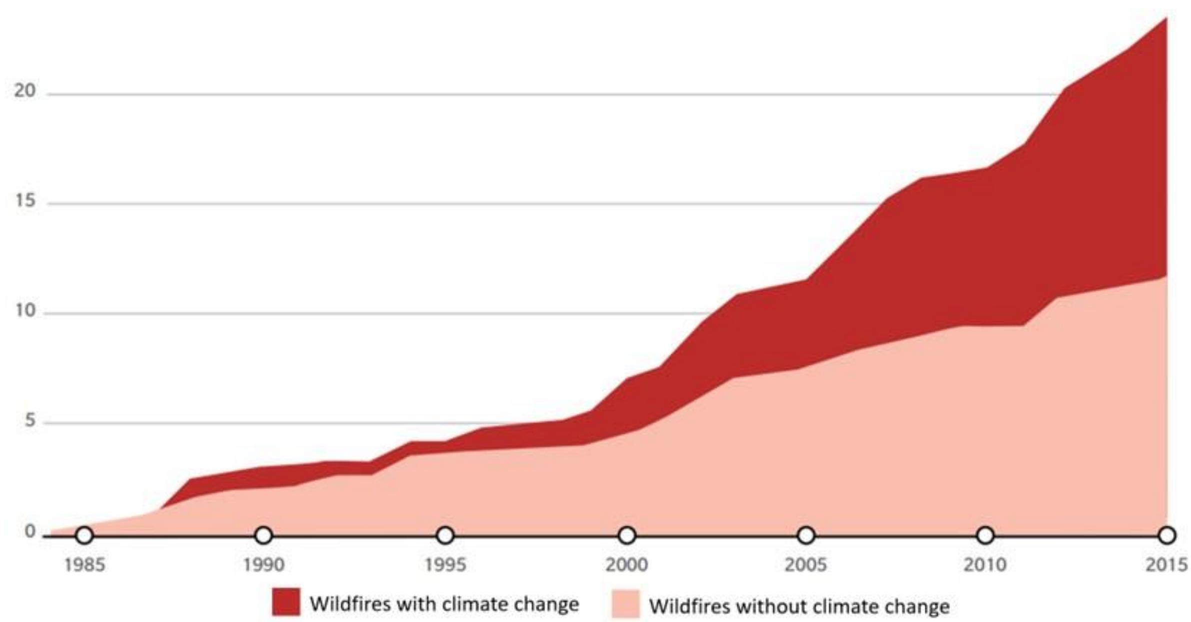
The observed changes in fire activity are driven by a combination of factors. In many cases, climate change exacerbates weather and fuel conditions that make it easier for fires to start and spread. Additionally, land-use and other human-induced changes to the landscape and the fire cycle also play a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

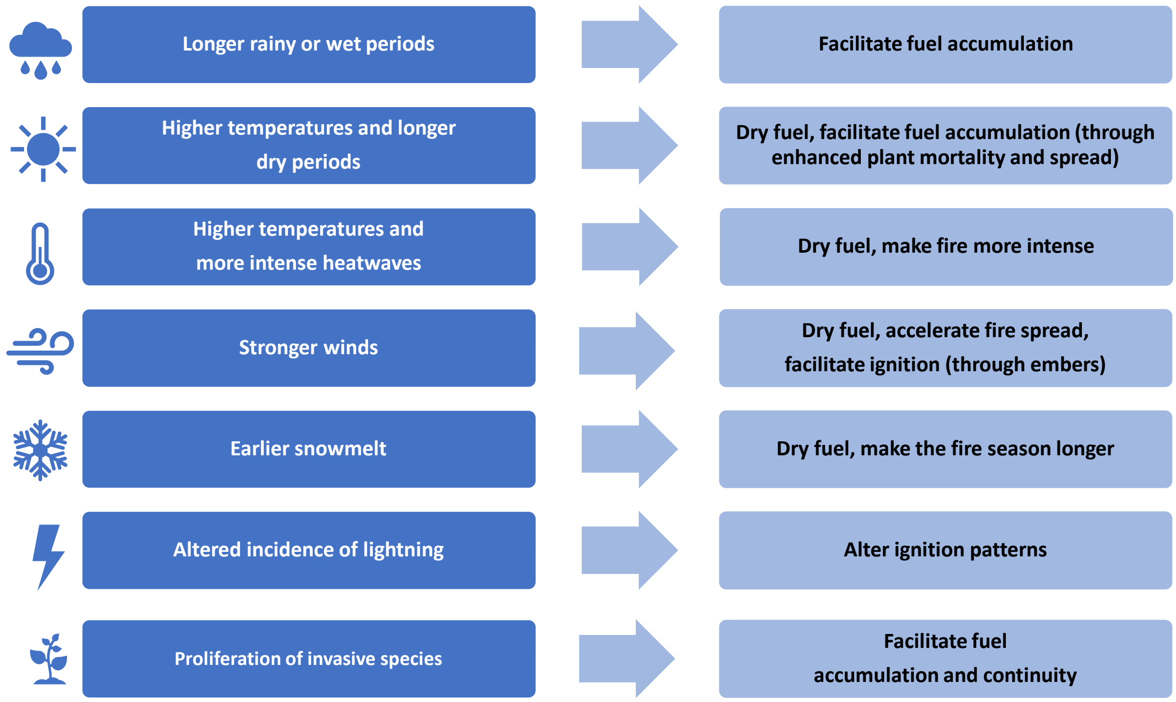
Million acres



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



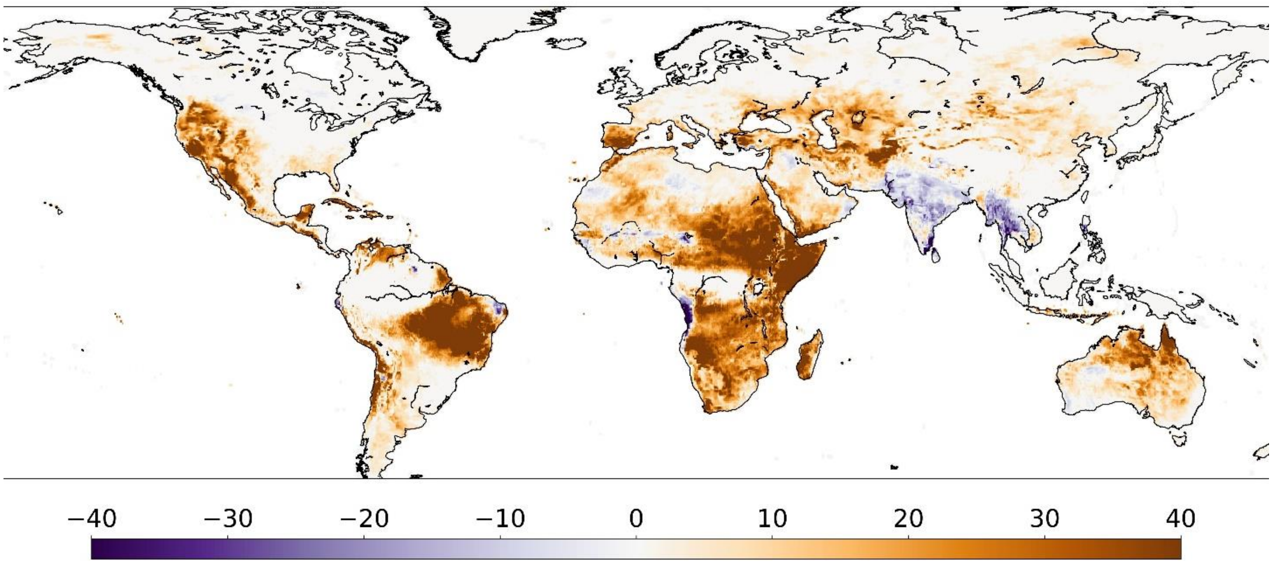
The effects of climate change on fire weather

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

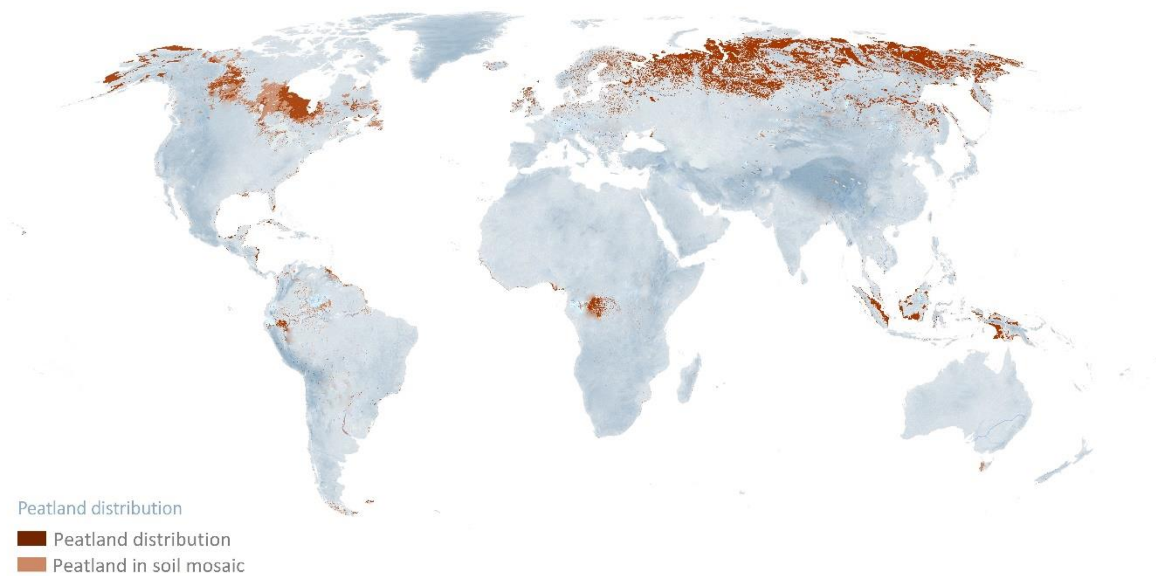
Land use and land management practices in the wildland-urban interface (WUI) and, more broadly, in rural and wildland areas play a key role in determining wildfire occurrence and behaviour, as well as the extent of wildfire impacts. At the same time, development in the WUI, as well as rural depopulation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

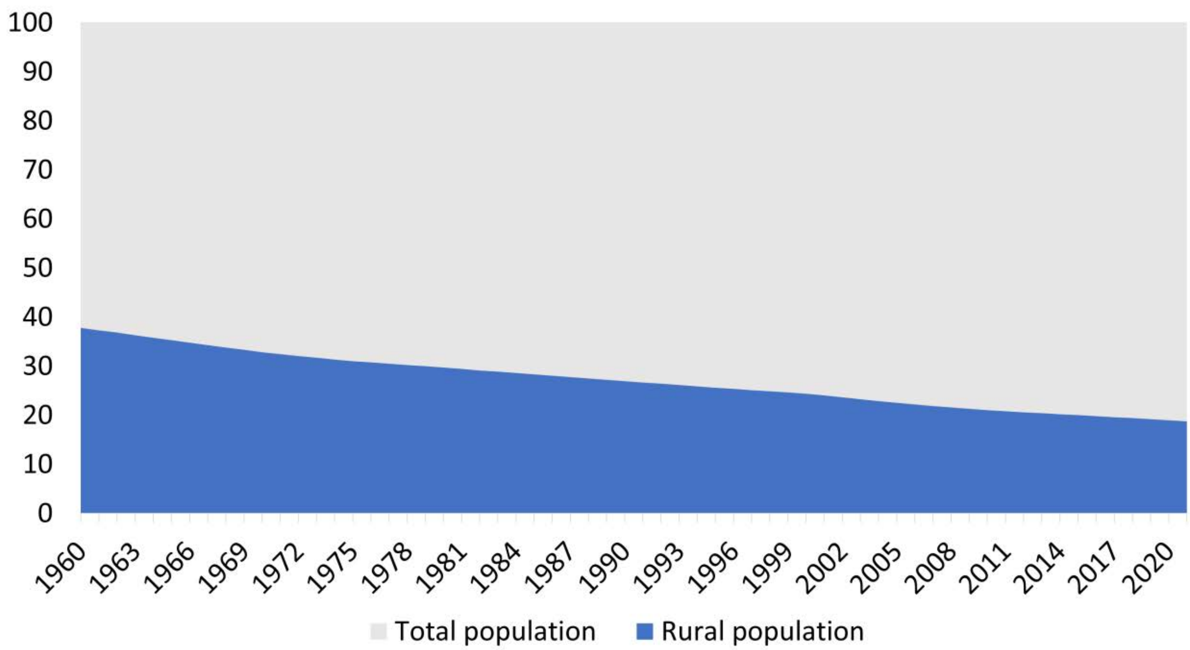
Development in the wildland-urban interface and rural depopulation

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

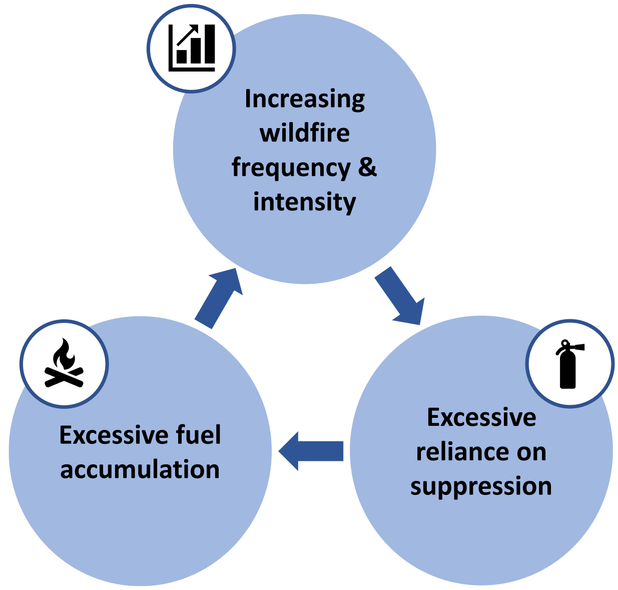


Note: World Bank estimations are based on the *United Nations Population Division's World Urbanization Prospects: 2018 Revision*.
Source: Based on data from the World Bank (n.d.[108]).

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.

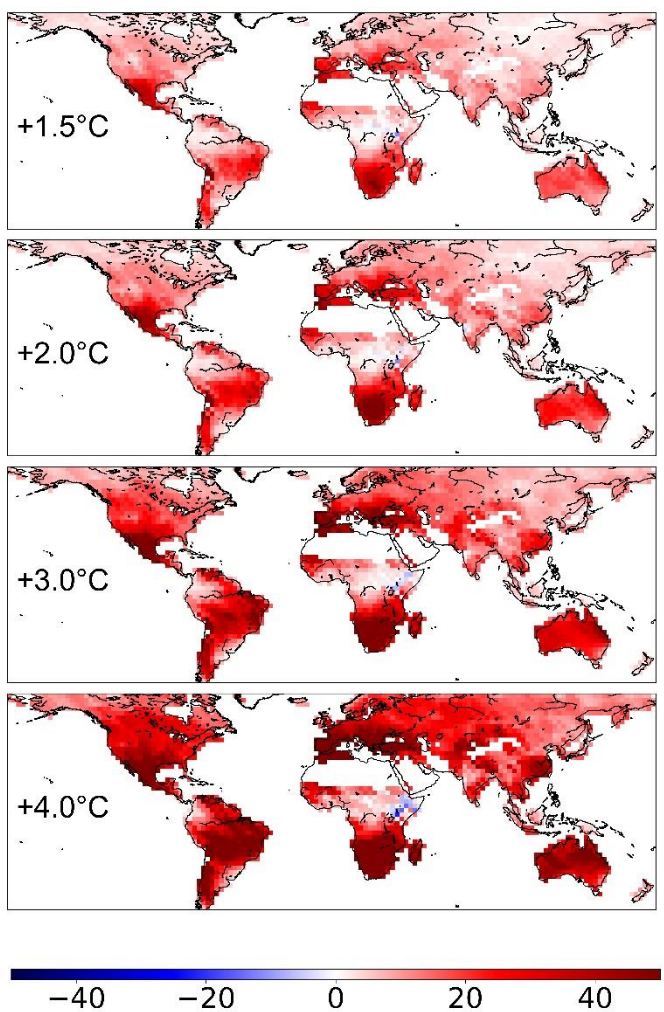
Climate change is likely to increase the occurrence of fire weather conditions on all continents. In south-eastern Australia, extreme fire weather conditions (e.g. periods with high temperatures and wind and low relative humidity and rainfall) are projected to become at least twice as frequent than they 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

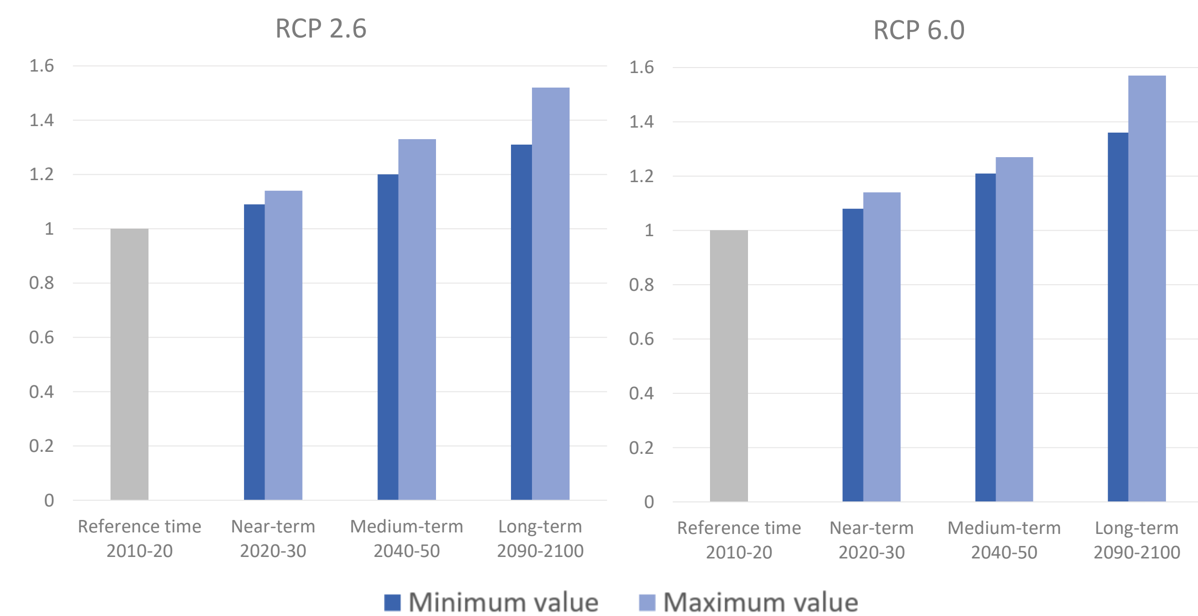
Change in the number of fire weather days, compared to 1860-1920



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]).

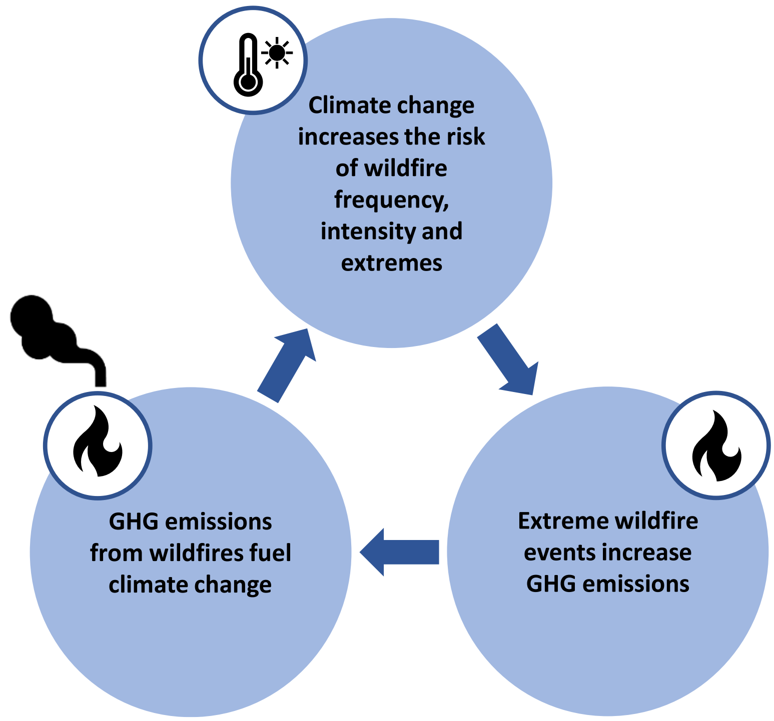
2.5. Understanding the environmental and socio-economic impact of wildfires

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

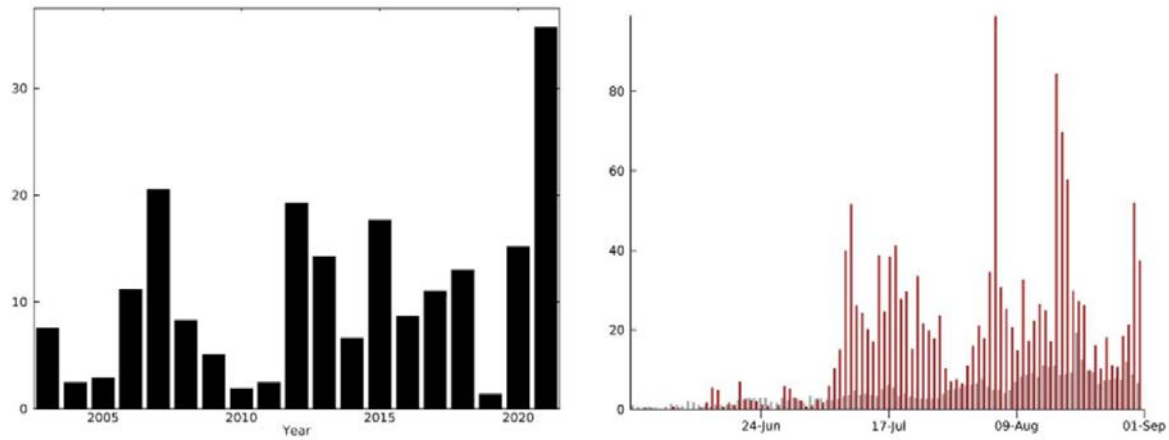


Note: GHG: greenhouse gas.
Source: Based on WRI (2022[41]).

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

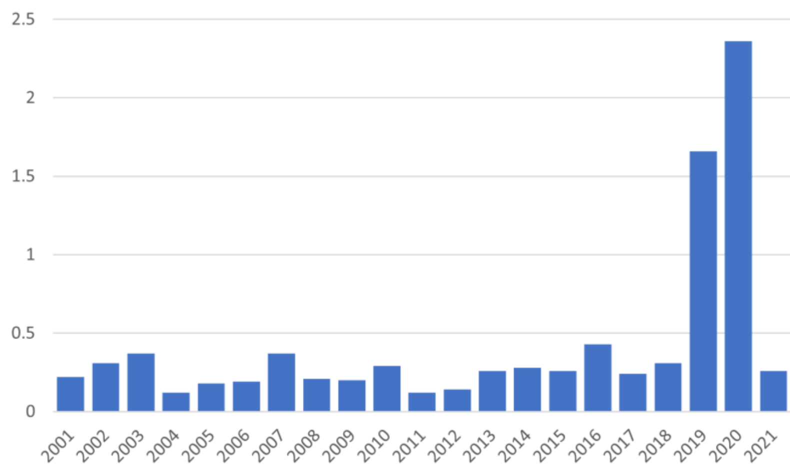
Changing wildfire patterns are increasingly affecting biodiversity, soil, and water availability and quality. Wildfire impacts vary significantly from one area to another, as different ecosystems are adapted to different wildfire regimes, i.e. to specific long-term patterns of wildfire activity. In some 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



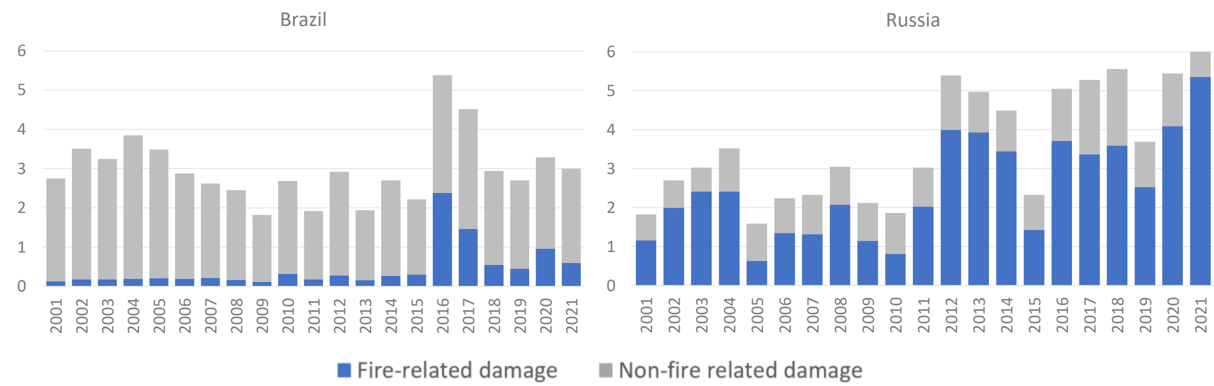
Notes: The peak in forest damage observed in 2019 and 2020 is correlated with the exceptionally large area burned during the 2019-20 wildfire season. While tree cover damage may be permanent in some cases, tree cover damage is temporary in others.
Source: Based on WRI (2021[147]).

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]).

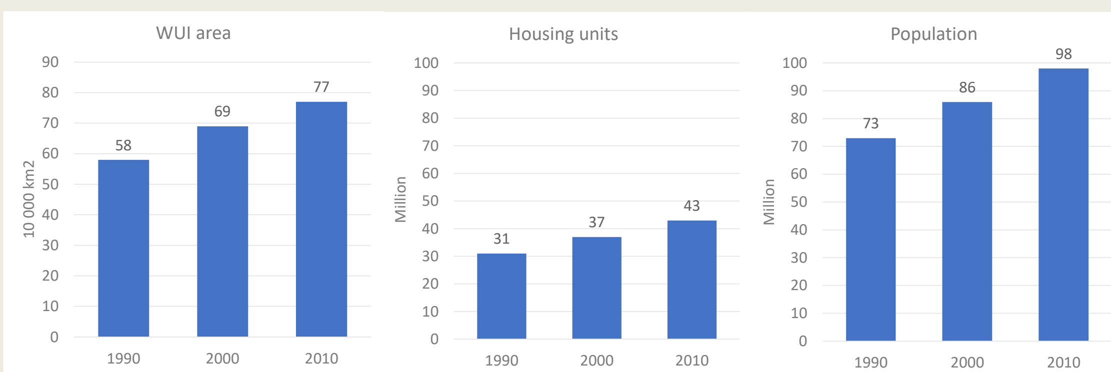
Infrastructure assets and networks have also been severely impacted by recent extreme wildfires, causing disruptions to service provision and continuity, and thus negatively affecting whole communities and economies. While estimates on the costs associated with infrastructure loss and damage remain limited, 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]).

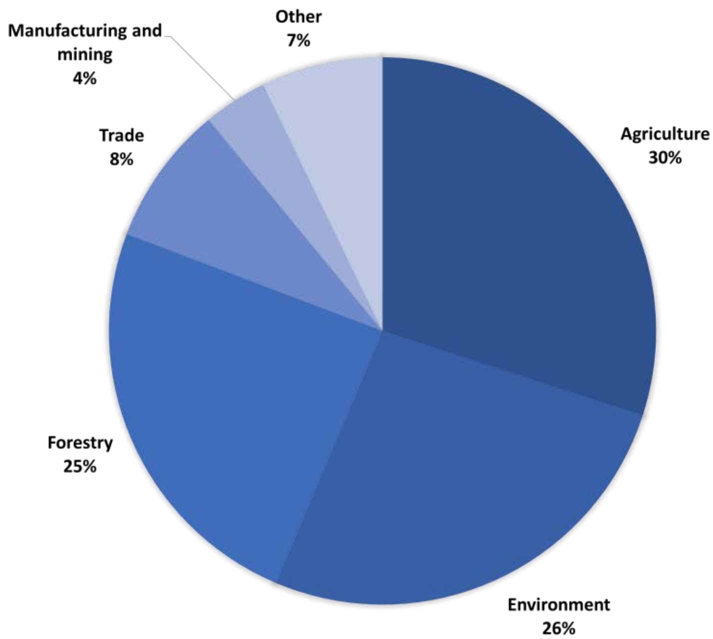
Wildfires can also cause significant economic losses for the tourism sector, as they can affect popular landscapes as well as the attractiveness and reachability of tourist destinations. For example, the 2019-20 wildfires in Australia were associated with tourism losses of USD 3 billion (DW, 2020[223]; 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)



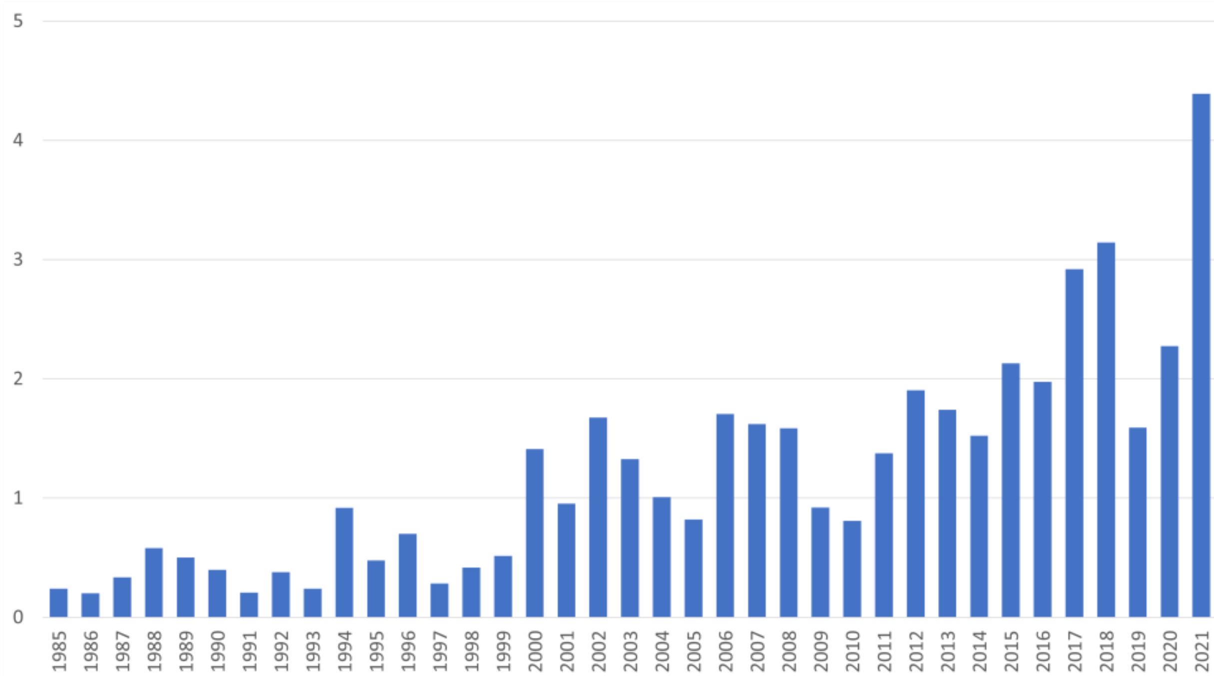
Notes: Percentages show the sectoral share of the total economic losses (i.e. over USD 1.3 billion) recorded between June and October 2015. The category "Other" covers tourism, transport, firefighting costs, health and education. The category "Environment" refers to biodiversity loss and the costs associated 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]).

3 Adapting policies and practices to extreme wildfires: A cross-country review

This chapter provides an overview of the trends in countries' policies and practices in response to the growing occurrence of extreme wildfires. The analysis is informed by the findings of five in-depth country case studies conducted in Australia, Costa Rica, Greece, Portugal and the United States, in addition to a desk review of policies and practices adopted by countries globally. The chapter assesses whether and how countries have adapted their policies and practices in light of the growing occurrence of extreme wildfires. In doing so, it highlights the indispensable and growing role prevention measures play in limiting the impacts and costs of extreme wildfires. The chapter identifies good practices and highlights findings and recommendations for designing a conducive enabling environment.

3.1. Introduction

The frequency and severity of wildfires, as well as the duration of the wildfire season, are on the rise in many regions around the world (see Chapter 2). In Australia, average wildfire frequency almost doubled between 1980 and 2020 and burned forest area increased by 350% between the early 1990s and 2018 (Canadell et al., 2021[1]). In the United States, wildfire severity (i.e. the degree of ecosystem impacts caused by a fire) increased eightfold between 1985 and 2017 across western forests (Parks and Abatzoglou, 2020[2]), while globally the duration of the fire weather season (i.e. the annual periods in which meteorological conditions are conducive to fire) increased by 27% between 1979 and 2019 (Jones et al., 2022[3]). The growing occurrence of wildfire extremes has challenged countries. Extreme wildfires have caused a high number of fatalities, with the extreme 2009 Black Saturday wildfires in Australia claiming over 180 lives (EM-DAT, 2023[4]). They have also caused detrimental impacts on ecosystems. In the 2017 wildfires in Chile, nearly 40% of critically endangered ecosystems suffered medium to high damage (van Hensbergen and Cedergren, 2020[5]). The 2018 Camp Fire in California, United States, caused an unprecedented USD 19 billion in economic damages, while economic damages from the 2019-20 wildfires in Australia reached USD 23 billion (EM-DAT, 2023[6]).

In response to the growing occurrence of extreme wildfires, countries have adapted and improved their wildfire management practices. In doing so, an overwhelming focus has been directed towards strengthening emergency preparedness and response capacities (Rodrigues et al., 2022[7]; Verkerk, Martinez de Arano and Palahí, 2018[8]). In the European Union, the EU Civil Protection Mechanism has helped countries strengthen disaster preparedness and response in times of crisis, including by co-ordinating wildfire suppression efforts and providing expertise and firefighting equipment (European Civil Protection and Humanitarian Aid Operations, 2022[9]). In an effort to detect wildfires early, countries have also improved their fire monitoring capacities. For example, the European Forest Fire Information System (EFFIS) and the Digital Earth Australia Hotspots monitoring system provide near-real time information on fire activity (EFFIS, n.d.[10]; OECD, forthcoming[11]). In Switzerland, a system of sensors provides hourly information on fuel moisture in selected forest patches (Müller, Vilà-Vilardell and Vacik, 2020[12]). Furthermore, early warning and evacuation systems have been improved in response to the gaps observed during extreme wildfires. For instance, Greece and Portugal introduced a text message system notifying anyone with cellular reception, including residents and visitors, of imminent wildfires. In Portugal, recent legislation also mandates the maintenance of ten-metre-wide buffer zones around main roads to ensure sufficiently large escape routes and access routes for firefighters (Komac et al., 2020[13]). Public budgets reflect this increase in emergency preparedness efforts. In the United States, federal funding for wildfire suppression has quadrupled, from an annual average of USD 425 million in 1985-99 to an annual average of USD 1.6 billion in 2000-19 (Roman, Verzoni and Sutherland, 2020[14]). Between 1998 and 2008, Greece doubled the public funding allocated for wildfire suppression, significantly scaling up aerial firefighting capacity (Xanthopoulos, 2015[15]; 2008[16]).

However, growing wildfire frequency and severity have shown the limits of emergency preparedness and response efforts in the context of climate change (Parisien et al., 2020[17]; European Commission, 2021[18]; Xanthopoulos, 2008[16]). Increasingly extreme wildfires have strained emergency response resources and limited their ability to contain impacts. This was observed, for example, during the extreme 2009 Black Saturday wildfires in Australia, which required more than one month of wildfire suppression to be completely extinguished (Swiss Re, 2015[19]). In 2018, the outbreak of multiple simultaneous wildfires in Greece challenged the effective deployment of firefighting resources, contributing to over 100 fatalities in Mati (Xanthopoulos and Athanasiou, 2019[20]). In light of future projected climate change, emergency preparedness spending in the Canadian provinces of Alberta, British Columbia and Ontario is expected to have to double by the 2071-2100 period to keep the current levels of success in wildfire response (Hope et al., 2016[21]).

These and other recent experiences with extreme wildfires highlight the need for a paradigm shift that brings adaptation and wildfire risk prevention efforts to the centre of wildfire management. In light of the decreasing marginal benefits of emergency preparedness spending, *ex ante* adaptation measures contain a large, untapped potential for improving countries' resilience to wildfires. This includes efforts that reduce the exposure of people and economic activities to wildfires by adapting land-use planning and building construction to growing wildfire hazard. It also includes measures to manage the landscape in a way that proactively reduces wildfire risk (e.g. fuel management, ecosystem protection, forest adaptation, etc.). This chapter assesses the degree to which countries have started to invest in wildfire risk prevention efforts.

3.1.1. Methodology

This chapter presents the findings of a cross-country comparative analysis, as well as the results of five country case studies conducted in Australia, Costa Rica, Greece, Portugal and the United States. The research focused on public policies and practices to reduce the risk of wildfires. The study sought to document, evaluate and compare countries' efforts. The main national counterparts consulted were the Ministries of Environment, with contributions from the national civil protection authorities and other key national and subnational agencies engaged in wildfire risk prevention. Annex A provides a list of stakeholders who engaged in the case study work, including through the elaboration of the case study reports, responses to the questionnaires, and participation in fact-finding interviews and fact-checking processes.

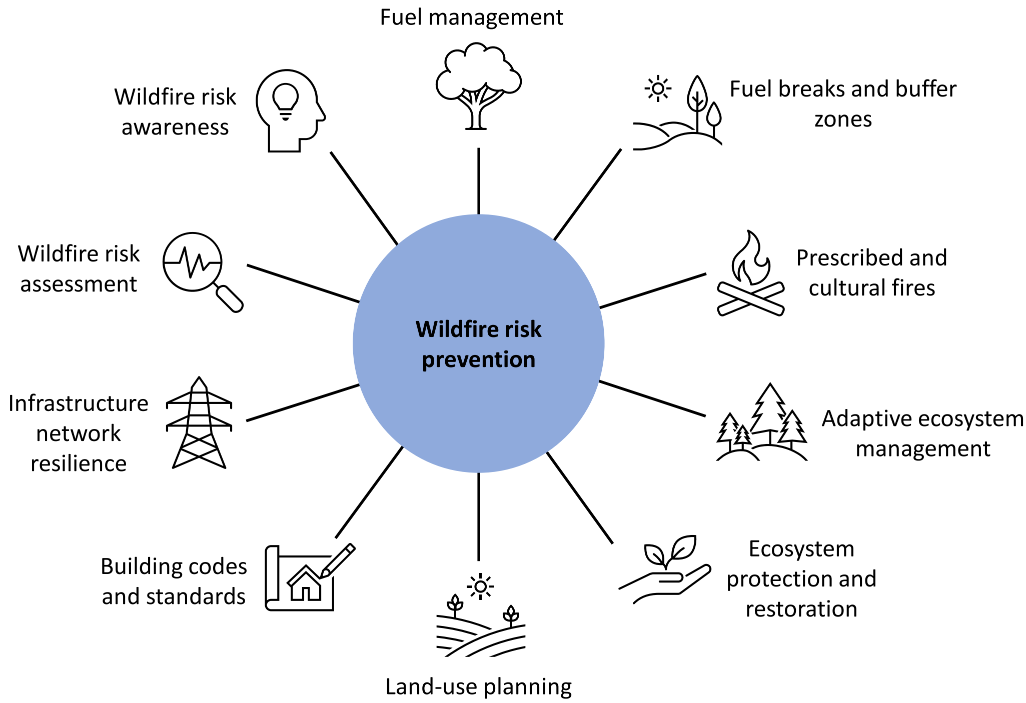
To ensure the comparability of the results of the country case studies, the background research, the country questionnaires that informed the background reports and the fact-finding missions were designed using the same structure and questions. The country questionnaire is included in Annex B of this report. The answers to these questions provide a comprehensive picture of how countries adapted their wildfire risk reduction efforts in response to the growing occurrence of extreme wildfire events.

The remainder of this chapter provides an overview of the case study findings, complemented by a review of existing policy practices around the world. It starts with an introduction of how wildfire risk prevention is fostered throughout the wildfire management cycle. It assesses countries' current efforts in wildfire risk prevention as compared to wildfire suppression. It then provides an overview of the enabling environment for wildfire management, including the financing, institutional and policy frameworks. The chapter highlights emerging good practices and identifies remaining challenges and policy gaps. The chapter's findings aims to inform policy makers and decision makers in all countries seeking to improve their wildfire risk management in the context of growing wildfire risk under climate change.

3.2. Scaling up wildfire risk prevention throughout the wildfire management cycle

In the context of growing extreme wildfire risk, scaling up climate change adaptation measures is critical to reducing the likelihood, behaviour and impacts of wildfires *ex ante* (UNISDR, 2017[22]). Wildfire prevention entails all measures that reduce wildfire hazard, as well as the exposure and vulnerability of communities and assets to wildfires, *ex ante*. Preventative measures include structural or "physical" measures that aim to manage fuel loads and continuity, such as fuel breaks, buffer zones, and prescribed and cultural fires, as well as ecosystem protection, restoration and adaptive management (see Section 3.2.1). In addition to physical measures, organisational measures are critical for reducing wildfire risk *ex ante*. These include regulations such as land-use planning or building codes and standards, as well as the fire-resilient management of infrastructure (see Section 3.2.2). Furthermore, wildfire prevention measures can also be incorporated into post-fire recovery, which plays an essential role in improving long-term resilience to wildfires (see Section 3.2.3). Wildfire prevention also entails adapting wildfire risk assessment to include expected climate change impacts on wildfire activity (see Section 3.2.4), as well as scaling up awareness-raising measures (see Section 3.2.5), which are needed if all-of-government and all-of-society are to contribute to reducing the impacts of extreme wildfires (Figure 3.1).

Figure 3.1. Reducing the risk of extreme wildfires through prevention measures



3.2.1. Fuel and ecosystem management for wildfire prevention

Fuel management is key to reducing wildfire risk and impacts, as it allows to manage the type and conditions of fuel loads in the landscape (Corona et al., 2015[23]). Fuel consists of live or dead biomass, e.g. vegetation, that is sufficiently dry to burn (see Chapter 2). Measures to manage fuel primarily include: the creation of fuel breaks and buffer zones; the use of prescribed and cultural fires ignited under safe conditions; the adaptive management of fire-prone ecosystems; and the protection and restoration of wildland ecosystems, such as forests and peatlands.

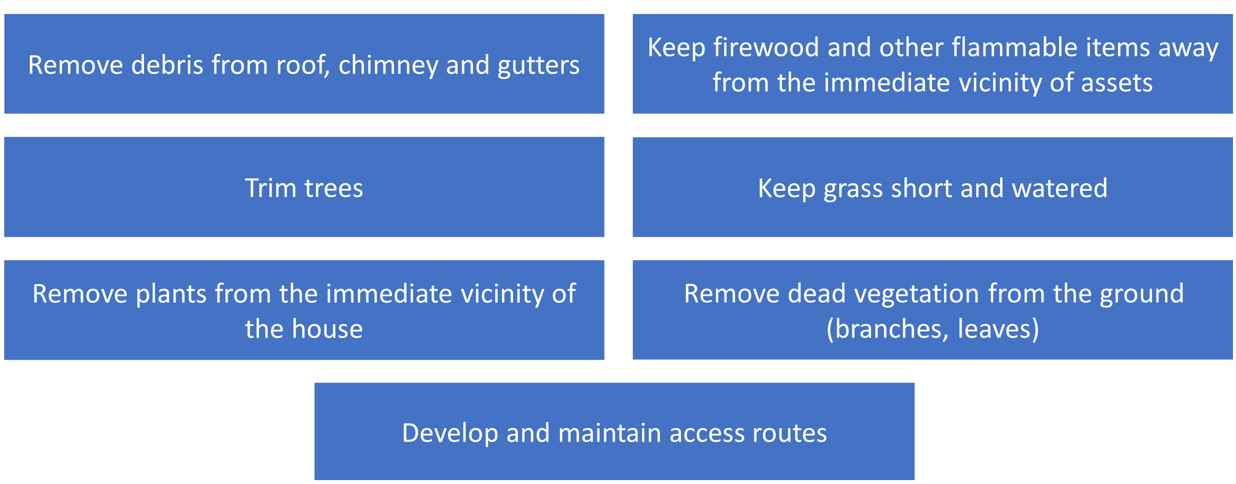
Fuel breaks and buffer zones

Managing fuel accumulation and continuity is particularly critical to reducing wildfire risk in the wildland-urban interface (WUI). Measures commonly used include buffer zones (or defensible spaces, i.e. strips of non-flammable land typically used to isolate exposed property, settlements and key infrastructure assets from flammable vegetated land) and fuel breaks, i.e. non-flammable strips of land (e.g. roads, rivers, crops, etc.) that can slow down or limit wildfire spread by breaking fuel continuity. Besides being a critical tool for wildfire prevention, these measures also facilitate emergency preparedness and response operations, as they provide evacuees and firefighters with protected corridors to transit (Rossi, Morvan and Simeoni, 2019[24]), as proven during recent extreme wildfires in the United States (US National Park Service, 2021[25]; Roman, 2018[26]).

Fuel breaks are widely used in several countries (Müller, Vilà-Vilardell and Vacik, 2020[12]; Ruiz-Mirazo, Robles and González-Rebollar, 2011[27]; Bertomeu, Pineda and Pulido, 2022[28]). In Australia and Portugal, the use of strategic networks of fuel breaks alternating different land covers (known as fuel mosaic areas) has significantly reduced landscape flammability and facilitated emergency response operations (OECD, forthcoming[29]; forthcoming[11]). Some governments have also bought private lands particularly exposed to wildfires to turn them into non-flammable fuel break areas. This occurred, for instance, in the aftermath of the extreme 2018 Camp Fire, when the municipality of Paradise, California acquired some of the most severely burned areas and transformed them into fire-resilient green spaces that serve as fuel breaks (Brasuell, 2021[30]).

The use of buffer zones to protect exposed assets and settlements is also widespread and has gained increasing attention in recent years (Roman, 2018[26]). Following particularly extreme wildfire events, both Greece and Portugal mandated the creation and maintenance of buffer areas in rural areas. In Portugal, these are mandatory for both new and existing buildings in WUI areas, while in Greece, new regulations require land tenants and owners in high-risk areas to remove excess vegetation and other flammable materials (e.g. firewood) from the perimeter surrounding their assets before the start of the wildfire season (OECD, forthcoming[29]; OECD, forthcoming[31]; Hellenic Republic, n.d.[32]). In Portugal, the Condomínio de Aldeia programme encourages fuel management in the surroundings of exposed WUI settlements and assets, promoting fire-resilient land-use changes through active land management and community engagement (OECD, forthcoming[29]; Presidency of the Council of Ministers, Portugal, 2021[33]). The programme also provides funding for managing fuel loads around properties and settlements and co-finances property owners' investments through national funding. In addition, economic incentives and government guidelines are sometimes used to encourage property owners to maintain buffer zones around their assets free from excess vegetation (e.g. by trimming trees, keeping grass short and removing plants from the immediate vicinity of the property) and other flammable fuels (e.g. debris and firewood piles) (Figure 3.2). For example, the state of Colorado, United States, offers tax incentives of up to USD 2 500 for property owners who implement prevention measures such as vegetation thinning and fuel breaks (Colorado Department of Revenue, 2022[34]).

Figure 3.2. Buffer zones and safety measures to reduce wildfire risk



Agricultural practices also play a key role in implementing fuel breaks and buffer zones. Non-flammable crops (e.g. fruit trees) can be used as fuel breaks, and agricultural practices such as grazing have also proven successful in reducing fuel loads (Ruiz-Mirazo, Robles and González-Rebollar, 2011[27]). Controlled grazing for fuel management is particularly common in Mediterranean countries such as France, Israel, Portugal and Spain (Komac et al., 2020[13]). Portugal and Spain encourage these practices through payment-for-ecosystem-services schemes, which reward local shepherds for undertaking grazing activity in public forests or around exposed settlements and assets (OECD, forthcoming[29]; Ruiz-Mirazo, Robles and González-Rebollar, 2011[27]; Varela et al., 2018[35]).

Despite their widespread uptake, the implementation of fuel breaks and buffer zones is subject to significant challenges. Local governments often lack the information and capacity to regulate, develop and maintain effective fuel break networks, as well as to enforce these requirements on private lands where regulations are in place. Land abandonment also poses significant challenges to the management of fuels on public and private lands, as it facilitates vegetation encroachment and fuel accumulation (Frei et al., 2020[36]; Moreira et al., 2020[37]; Ruiz-Mirazo, Robles and González-Rebollar, 2011[27]). Over the past century, land abandonment in the Mediterranean region has been associated with significant fuel build-up, which has contributed to an increase in wildfire risk in the region (Mantero et al., 2020[38]). This was the case, for example, in Portugal, where between 1960 and 2021 the rural population decreased from 5.7 million to 3.4 million, i.e. from 65% to 33% of the total population, leaving large portions of rural land unmanaged (World Bank, n.d.[39]; OECD, forthcoming[29]). Extreme wildfires also reduce the effectiveness of fuel breaks and buffer zones. For example, during the 2019-20 extreme wildfires in Australia, as well as during recent extreme wildfires in Andalusia, Spain, strong winds coupled with exceptionally intense wildfires allowed embers to overrun fire breaks (Nolan et al., 2021[40]).

Prescribed and cultural fires

Prescribed fires consist of small-scale, low-intensity, controlled fires ignited to achieve specific land management objectives, including wildfire prevention and ecological or agricultural management (Belcher et al., 2021[41]; Santin and Doerr, 2016[42]). In the context of wildfire prevention, prescribed fires are implemented before the start of the wildfire season to reduce fuel loads. Yet, controlled fires can also be used during the wildfire suppression phase to contain or control the spread of ongoing wildfires, a technique known as backfires. Countries such as Australia also encourage early-season prescribed fires to contain their annual wildfire-related greenhouse gas emissions, as controlled low-intensity fires release less carbon than intense wildfires occurring in the dry season (IPCC, 2022[43]; Lipsett-Moore, Wolff and Game, 2021[44]).

The extent to which prescribed fires are used for wildfire prevention varies significantly across countries (Montiel and Kraus, 2010[45]). For example, prescribed fires have been used for many decades in Australia, Canada and the United States (Burrows and McCaw, 2013[46]; Melvin, 2021[47]), while in Europe their use remains restricted (e.g. in France and Portugal) or completely forbidden (e.g. in Greece) (OECD, forthcoming[29]; forthcoming[31]; Corona et al., 2015[23]; European Commission, 2018[48]; Fernandes et al., 2013[49]). Restrictions on the use of prescribed fires usually stem from security or environmental concerns about the impact of such measure on air quality and the risk of prescribed fires slipping out of control (Huang et al., 2019[50]; USDA, 2018[51]). This high-risk perception often goes hand-in-hand with a limited awareness of the benefits of prescribed fires. To overcome these challenges, France and Portugal have recently set up specific legal frameworks to regulate active fire use, which include systems for the professional accreditation of prescribed fire managers (Montiel and Kraus, 2010[45]). The use of backfires is rather common in Mediterranean countries such as Cyprus, Portugal and Spain (OECD, forthcoming[29]; Montiel and Kraus, 2010[45]) and has recently been allowed in Greece (OECD, forthcoming[31]).

In addition to prescribed fires, other types of controlled fires on private lands can help reduce fuel accumulation and, thus, wildfire risk. These include agricultural fires ignited by farmers to regenerate crops and pastures, clear the land, and dispose of agricultural waste, as well as the cultural fires[1] ignited by indigenous groups and local communities (Box 3.1). The use of agricultural fires is regulated by national or subnational laws that define when, where and under which conditions prescribed fires can be used. In many cases, agricultural fires are forbidden during the wildfire season and can only be implemented after obtaining a permit from the relevant authorities (Müller, Vilà-Vilardell and Vacik, 2020[12]; Department of Agriculture, Food and the Marine, Ireland, n.d.[52]). To limit the use of fire for opportunistic development purposes, countries such as Ireland only allow the active use of fire on lands that will then be used for agricultural purposes (Department of Agriculture, Food and the Marine, Ireland, n.d.[52]).

However, stricter regulations on the active use of fire and better enforcement of such regulations still lack in many cases. Climate change only adds to these gaps, as longer fire seasons and less predictable weather patterns hamper the effectiveness of season-bound restrictions on the active use of fire. Besides, while regulating and restricting the use of fire in high-risk periods is critical to reducing wildfire risk, securing an ecological amount of fire activity in the landscape is important, too, to avoid the excessive accumulation of fuel. As in many cases liability concerns regarding the risk of prescribed fires slipping out of control have discouraged private landowners from using fire on their lands, some governments – e.g. the state of California – have lifted liability laws for wildfires resulting from escaped prescribed fires, thus enabling the use of prescribed fires by indigenous groups to reduce wildfire risk (OECD, forthcoming[53]; Weir et al., 2020[54]).

Box 3.1. Harnessing cultural fires and indigenous knowledge for wildfire prevention

For thousands of years, local communities and indigenous people have used fire to manage ecosystems (Christianson, 2015[55]; Firesticks, 2019[56]). Some governments have engaged with indigenous and local communities to enable and integrate the use of these practices into broader wildfire prevention plans. This has been the case, for example, in Australia, California, and the Bolivarian Republic of Venezuela (Pardo Ibarra, 2020[57]; OECD, 2021[58]). In Australia, the use of cultural fires was associated with a reduction of 50% in the area burned between 2000-06 and 2013-19 (OECD, forthcoming[11]).

At the same time, countries have also set up programmes to facilitate the integration of local and traditional knowledge into policy processes. For example, collaborations between government officials, firefighters and indigenous communities were set up in Australia and Brazil, as well as in California and Hawaii (United States), to scale up the competences of local firefighters, improving land-use planning decisions and creating participatory local fire management plans (OECD, 2021[59]; 2021[58]; Sommer, 2020[60]). In Brazil, the collaboration of government officials and indigenous people was associated with a 40-57% reduction in wildfire risk in three large territories (as compared to the years preceding the programme implementation) while also improving relations between the government and indigenous communities (FAO, 2021[61]).

Sources: Christianson (2015[55]); Firesticks (2019[56]); Pardo Ibarra (2020[57]); Sommer (2020[60]); OECD (2021[59]; 2021[58]; forthcoming[11]); FAO (2021[61]).

Adaptive ecosystem management

Active and adaptive forest management can significantly reduce wildfire risk. Planting fire-resilient species and excluding particularly fire-prone species in high-risk areas plays a key role in reducing landscape flammability and increasing vegetation resilience to wildfires (Fitzgerald and Bennett, 2013[62]). These interventions are particularly important in fire-prone areas where highly flammable non-native species prevail. For example, in Portugal, the total area of eucalyptus forests grew by 62% between 1990 and 2017 (APA, 2020[63]) and currently accounts for 26% of the total forest area of mainland Portugal, according to the country's latest forest inventory (ICNF, 2016[64]; 2021[65]; OECD, forthcoming[29]). To address this challenge and reduce landscape flammability, Portugal has established a pilot payment-for-ecosystem-services scheme that rewards private landowners who plant native species (OECD, forthcoming[29]).

Other widely used ecosystem-based interventions for wildfire risk reduction include the use of vegetation thinning, i.e. the selective removal of some parts of the vegetation to reduce excessive forest density. Forest thinning makes forest stands healthier and more resilient to wildfires (Figure 3.3) and other risks, such as pest outbreaks (Oregon Forest Resources Institute, 2023[68]). For instance, in Spain, the use of forest thinning, along with prescribed fires, has significantly reduced the wildfire spread rate and severity in forested lands (Piqué and Domènech, 2018[69]). Yet, existing land ownership structures often hamper the effectiveness of these measures (Box 3.2). Besides, in some areas (e.g. in the Alpine region), forest owners often lack the necessary awareness and skills for adaptive forest management, which can lead to inappropriate levels or types of forest management. Local governments themselves may, in some cases, lack the capacity to manage (or mandate the management of) forests in line with local ecological needs and characteristics.

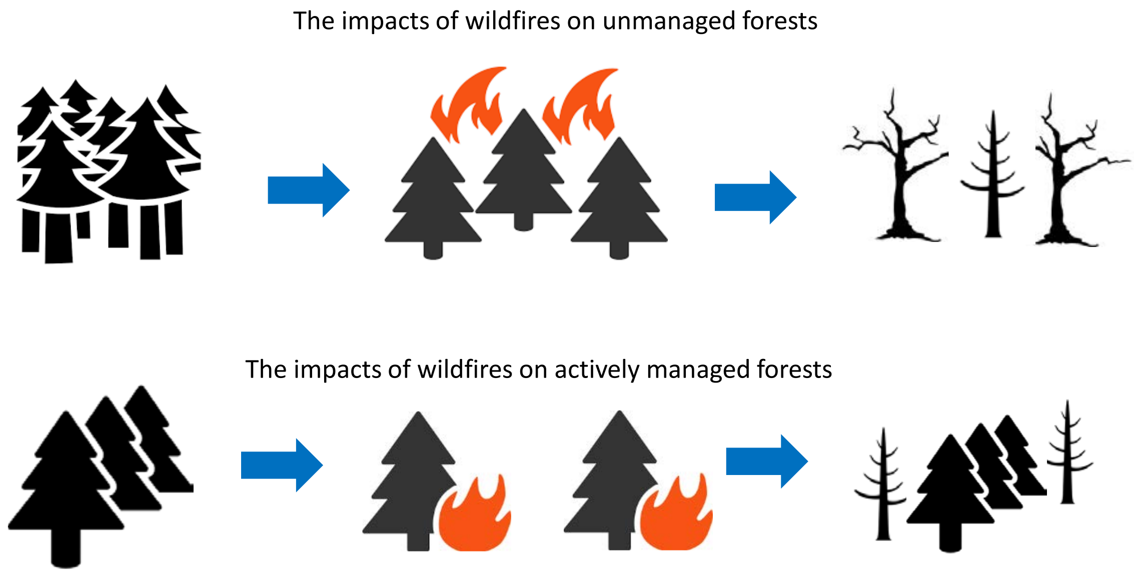
Box 3.2. Managing fuel in private lands: The challenge of land ownership

Engaging with private land owners is a critical component of wildfire prevention, as they are responsible for implementing fuel management measures on private land. This is particularly important in countries where land or forests are largely owned by private entities – such as in Portugal, where only 3% of forested land is owned by the state. Yet, in several countries, the enforcement of existing requirements concerning active forest management is challenged by unknown or unclear land ownership, which raises the question of who should manage fuel accumulation when landowners are not clearly defined. For example, in Portugal, over 20% of forestlands have no or unknown ownership and only 46% of forest areas are included in the land registry. In Greece, similar challenges are further complicated by the unclear delineation of forest areas (APA, 2020[63]; Triantis, 2022[66]; OECD, forthcoming[31]; forthcoming[29]).

To tackle these challenges, Portugal has recently passed a law that enables the state to carry out fuel management activities in forestlands where the owner is unknown or where owners fail to carry out the requested fuel management efforts, a practice known as “forced tenancy”. In addition, the Bolsa de Terras programme encourages public and private lands to be made available for lease or sale to facilitate their active management via agricultural, forestry and silvipastoral activities (OECD, forthcoming[29]).

Sources: OECD (forthcoming[29]; forthcoming[31]); APA (2020[63]); Triantis (2022[66]); The Nature Conservancy and Willis Watson Towers (2021[67]).

Figure 3.3. The benefits of active fuel management for wildfire risk reduction in forested areas



Ecosystem protection and restoration

Protecting and restoring ecosystems is critical for wildfire risk prevention. Healthy forests, peatlands and other wildland ecosystems are usually less prone to wildfire ignition and spread and more resilient to the potential negative impacts of wildfires. They also contribute to other societal goals, including the conservation of biodiversity and climate change mitigation (OECD, 2021[70]).

Ecosystem degradation, aggravated by climate change, has made many ecosystems more prone to fire. For example, forest degradation and fragmentation due to excessive logging, overgrazing and deforestation can reduce forest humidity and increase atmospheric temperature, enhancing the risk of extreme wildfires (Wester Fire Chiefs Association, 2023[71]). Peatland drainage and associated drying can also enhance wildfire risk, as dry peat is highly flammable and wildfires in peatlands can burn underground and are thus difficult to extinguish (Borneo Nature Foundation, n.d.[72]). For example, the large extent of burned area observed during the 2016 wildfires in Ghana was associated with forest degradation, which by reducing fuel moisture exacerbated the impacts of drought and contributed to the spread of the wildfire. Consequently, the extent of burned area in degraded forest stands was found to be higher than that experienced by healthier ones (Dwomoh et al., 2019[73]). Similarly, low water levels in Indonesia's degraded peatlands contributed to the occurrence and severity of the 2015 wildfires by making the landscape more flammable (UNEP, n.d.[74]).

Following particularly extreme wildfires in recent years, protecting and restoring forests and peatlands have become a key element in many countries' wildfire risk prevention efforts. Forest restoration efforts such as reforestation, tree diversity restoration, and the control of invasive and underbrush species are at the centre of wildfire risk prevention efforts in Costa Rica (Box 3.3), Gambia and South Africa (Global Canopy, 2021[75]; UNEP, UNEP-DTU Partnership, World Adaptation Science Program, 2021[76]; Republic of South Africa, 2022[77]). The United States has also recently announced a new partnership among federal and state agencies and indigenous communities to enhance nature conservation and reforestation efforts for wildfire risk reduction (Government of the United States, 2022[78]). In the aftermath of the 2015 extreme wildfires, Indonesia established an agency dedicated to peatland restoration and pledged to restore the hydrological balance of over 2 million hectares of peatland in an effort to reduce future wildfire risk and greenhouse gas emissions (Ward et al., 2021[79]; Wijaya et al., 2016[80]). Countries have also adopted strict rules to protect forests and peatlands from deforestation, degradation and land-use changes that could lead to higher wildfire risk. In the aftermath of the 2015 wildfires, Indonesia issued a permanent moratorium on primary forest and peatland conversion permits (Wijaya et al., 2016[80]), while in 2022, the United States issued an executive order to protect old-grown forests to reduce wildfire risk (Government of the United States, 2022[78]).

Box 3.3. Wildfire risk prevention in protected areas: The case of Costa Rica

Costa Rica is recognised globally for its national system of protected areas and natural parks, which cover over 25% of its continental territory. In these areas, the National System of Conservation Areas (SINAC) – i.e. the agency in charge of designing and implementing national strategies and projects in protected areas – promotes wildfire prevention by encouraging active ecosystem management. In the Palo Verde National Park, ecosystem-based interventions include the management of fuel accumulation through controlled fires, extensive grazing and the mowing of vegetation. Prescribed fires are also used every year in the Santa Rosa National Park as part of the local wildfire protection programme. In some protected areas, activities are also carried out to recover water bodies, estuaries and seasonal wetlands. In and around the territory of protected areas, SINAC also works to raise public awareness of the ecological value of protected areas and the risks posed by wildfires in the context of climate change. It also undertakes research on the fuel characteristics and wildfire drivers in Costa Rica's protected areas. Since 2013, Costa Rica has also engaged in technical studies to identify the areas projected to be most affected by wildfires under future climate change.

Sources: SINAC (n.d.[81]); MINAE (n.d.[82]); Espinoza (2016[83]).

Despite some progress, there is scope to strengthen efforts to protect and restore wildland ecosystems from unsustainable land-use practices. The lack of compliance with existing regulations is a key challenge in many of the countries suffering from high deforestation rates. For example, Brazil faces major compliance issues in the application of its national Forest Code, which requires private landowners in ecologically sensitive areas to maintain a share of their lands undeveloped (Stefanes et al., 2018[84]). Low compliance has been associated with insufficient monitoring and enforcement activities, as well as incomplete rural land registries, which in the Brazilian Amazon provide clear land ownership information for only 10% of all private lands (The Nature Conservancy, n.d.[85]).

Major policy gaps also remain in the restoration of natural fire activity, which in some areas is an important pillar of ecosystem restoration. While fire-adapted ecosystems may benefit from natural wildfire occurrence, countries often tend to favour the immediate suppression of wildfires, even in remote areas where low-intensity natural wildfires do not pose an immediate threat to communities or exposed assets. This insufficient level of natural fire activity in fire-adapted ecosystems is often linked to a lack of technical knowledge and skewed risk perception and can have long-term implications on ecosystem health and resilience to future wildfire risk (UNEP, 2021[86]). The excessive reliance on wildfire suppression has been associated with ecosystem imbalances in many areas, including in Brazil, Greece, the United Republic of Tanzania and the United States (Kelly et al., 2020[87]; Xanthopoulos, 2008[16]).

3.2.2. Land-use planning and building regulations for wildfire prevention

Land-use planning and building regulations play a critical role in wildfire risk prevention, as integrating wildfire hazard information into land-use decisions can directly reduce the exposure and vulnerability of people and assets.

Land-use planning for wildfire prevention

Land-use planning allows limiting development or mandating specific prevention measures for new and existing constructions in fire-prone areas. In particular, land-use zoning and regulations on building height and density within each land parcel can help contain wildfire risk, reducing fire spread and building resilience to wildfire impacts (Ganteaume and Long-Fournel, 2015[88]).

Land-use zoning informed by wildfire risk assessments (see Section 3.2.4) has been widely used to reduce human and asset exposure to wildfire risk. For example, in Portugal, the construction of new permanent buildings is forbidden in areas characterised by “high” and “very high” wildfire hazard (OECD, forthcoming[29]; Presidency of the Council of Ministers, Portugal, 2021[33]). Exceptions to this ban are only granted in specific cases and when risk reduction measures, such as buffer zones, are implemented. In France, wildfire risk prevention plans regulate development in fire-prone areas, banning development in areas where property protection is impossible and only allowing it where exposure and vulnerability can be reduced via specific wildfire risk reduction measures, such as the use of fire walls or non-flammable building materials (Kocher et al., 2017[89]).

Nonetheless, due to high demand for residential and touristic development, asset construction in the WUI continues to grow in several countries. For example, between 1990 and 2010, the WUI area and population in the United States increased by 33-34%, contributing to the devastating wildfire impacts observed in recent years (Radeloff et al., 2018[90]). These trends, which are particularly common in coastal areas or metropolitan areas expanding into fire-prone areas, only exacerbate the low planning and enforcement capacity that characterises some local governments. In Greece, high development demand in the WUI combined with unclear land type categorisation have facilitated informal housing development in high-risk areas, with an average of 31 000 informal buildings built illegally every year between 1991 and 2001 (i.e. one-quarter of total development occurred in the country in the same period) (Blandford, 2019[91]; Triantis, 2022[66]). During the extreme Mati wildfires in 2018, the high number of assets that did not have building permits contributed to the severity of the fires, resulting in a building destruction rate of 80% (Hellenic Republic, 2021[92]; Blandford, 2019[91]; OECD, forthcoming[31]).

Building codes and standards for wildfire-resilient assets

Building codes and standards regulate how physical assets such as houses and infrastructure should be built or managed. For example, they can mandate the use of non-flammable materials for buildings and fences or the upgrade and maintenance of assets using hard reinforcement and defensive measures (e.g. requirements on the fireproofing of windows, vents, chimneys, etc.) (Figure 3.4). Altogether, these practices are particularly effective in reducing the likelihood of assets being burned, as in many cases buildings are ignited by flying embers rather than by direct contact with the wildfire itself (Insurance Institute for Business & Home Safety, 2019[93]). A recent study suggests that structural improvements alone can reduce wildfire risk by up to 40%, reducing losses by five times compared to highly flammable structures (Czajkowski et al., 2020[94]). This was demonstrated during the 2018 Camp Fire in California, when only 11.5% of older houses (i.e. houses built before 1990) survived the fire, while 44% of the houses built after 2008 (i.e. a year in which stricter building regulations were implemented) survived the fire (Knapp et al., 2021[95]). Similarly, during the extreme Attica fires in Greece, the village of Neos Voutzas – a highly exposed settlement mostly built out of high-quality building materials – suffered limited damage, while in the neighbouring village of Mati, 80% of constructions were completely destroyed (Hellenic Republic, 2021[92]; OECD, forthcoming[31]).

Figure 3.4. Building reinforcement options for wildfire-resilient housing

Source: Based on Lynch, McMahon and Sassian (2019[96]).

Building codes and standards are used to contain wildfire impacts and costs several in high-risk areas. Legislation mandating structural protection measures and fire-proof building design, including the use of non-flammable materials and non-flammable roofs and fences, is in place in Greece and Portugal (OECD, forthcoming[29]; forthcoming[31]; Hellenic Republic, n.d.[32]). In New Zealand, the national government implemented building regulation clauses to limit the spread of wildfires and ensure the structural stability of buildings during wildfires (Government of New Zealand, 2021[97]). In California, new assets built in fire-prone areas are subject to building code requirements, including on defensible space and construction materials and methods (ICC Digital Codes, n.d.[98]; OECD, forthcoming[53]). Besides, in the United States, the application of the International Wildland-Urban Interface Code (IWUIC),[2] a model code designed to support land development regulation in the WUI, is mandatory for every new federal building of a certain size built in WUI areas (US Fire Administration, 2016[99]; OECD, forthcoming[53]). In Australia, voluntary best-practice guidelines on wildfire-resilient construction are also in place (OECD, forthcoming[11]). In Boulder County, Colorado (United States), the local government funds house inspections that provide tailored recommendations for risk prevention measures that can be adopted at the property level (e.g. fire-proof roofs and windows, non-flammable building materials, buffer zones). Property owners who implement these measures receive certificates that enable them to get insurance coverage for wildfire risk (Boulder County, n.d.[100]; Kunreuther and St. Peter, 2020[101]).

However, despite recent improvements, the development and implementation of building regulations are still limited. In many cases, existing building codes and standards only apply to new developments, leaving a regulatory gap for buildings and assets that already exist in high-risk areas. Besides, building codes and standards are sometimes developed in the form of non-legally binding guidelines to be adopted on a voluntary basis. Besides, in some cases, subnational governments lack the capacity to develop fire-resilient land-use and building regulations. To address this challenge, in Colorado, programmes are in place to encourage the integration of risk reduction measures into county-level land-use and building regulations (Planning for Hazards, n.d.[102]). In addition, where building codes exist, their enforcement remains a key challenge (IBHS, 2019[103]), mostly due to limited monitoring capacity and resources at the local level. To tackle low compliance with existing building regulations, some local governments in Oregon, United States, have set up fines for non-compliance (Roman, 2018[26]).

Infrastructure design, operation and management

Infrastructure managers and operators can play a key role in wildfire risk prevention. While wildfires can have negative impacts on infrastructure by destroying or damaging exposed assets and interrupting infrastructure services (see Chapter 2), poorly planned or managed infrastructure in WUI areas can, in turn, increase wildfire risk (IPCC, 2022[43]). In many cases, infrastructure such as railways and electricity lines represent a key cause of wildfire ignition. For example, in California, utility failures caused the ignition of 40% of the most destructive wildfires in the state's history, including the devastating 2018 Camp Fire (Legislative Analyst's Office, 2021[104]). Five of the ten wildfires that caused the most destruction in California between 2015 and 2019 were linked to failures in the electrical network of one single energy utility, whose assets were found to be in a state of neglect and did to meet state requirements on infrastructure maintenance (Penn, Eavis and Glanz, 2019[105]). As conditions conducive to extreme wildfires grow in the context of climate change, similar events only become more likely, making climate-resilient infrastructure design and management ever more crucial to reduce wildfire risk (Lyster, Farber and McFadden, 2022[106]). At the same time, it is essential to build critical infrastructure networks that are resilient to current and future wildfire risk, ensuring that their services and operations continue running as much as possible even during wildfire events (OECD, 2019[107]).

To build infrastructure resilience to wildfires, countries have adapted regulations mandating infrastructure operators to abide by safety rules and develop contingency plans that can reduce wildfire risk and impacts. For example, Canada requires its two largest train companies to reduce train speed during high wildfire risk periods, as well as to remove flammable materials from the tracks and prepare their own wildfire risk reduction plans (Scherer, 2021[108]). In addition, some national and subnational governments set specific programmes and targets to ensure wildfire-resilient infrastructure development. Following the extreme 2009 wildfires, the state of Victoria, Australia, established an AUD 750 million Powerline Bushfire Safety Program, which has reduced wildfire risk from powerline ignition by upgrading the electricity distribution network and regulating infrastructure management in high-risk areas (OECD, forthcoming[11]; Victoria State Government, 2022[109]). In Portugal, the Climate Change Adaptation Action Plan sets the ambition to have 50% of its transport infrastructure companies develop an adaptation or contingency plan for extreme events by 2030 (OECD, forthcoming[29]). Furthermore, infrastructure project plans in Portugal must consider climate scenarios to be approved and, in most cases, critical infrastructure managers are legally required to manage wildfire risk around their assets (OECD, forthcoming[29]).

Infrastructure managers and operators have also taken voluntary measures to reduce wildfire risk. For example, Portugal's largest generator and provider of energy, Energias de Portugal, has developed its own wildfire hazard reduction plan, which includes interventions on fuel management, asset management, wildfire surveillance and awareness-raising activities. Since 2013, the plan has contributed to reducing the burned area in Sabor Valley from an average of 210 hectares per year to 14 hectares per year (UNDRR, 2021[110]). In Southern California, San Diego Gas & Electric, a public utility provider, has installed additional weather stations, cameras and other technology to monitor real-time wildfire risk and adapt operations accordingly (Penn, Eavis and Glanz, 2019[105]). Overall, while regulations that require infrastructure managers and operators to abide by certain safety rules are in place in some cases, in many countries such measures are implemented on a voluntary basis.

3.2.3. Mainstreaming wildfire prevention in post-fire recovery measures

The period following a destructive wildfire offers a window of opportunity to integrate risk prevention considerations into recovery efforts and build long-term resilience (Schumann et al., 2020[111]). Indeed, the policy and management decisions taken in the aftermath of a wildfire can affect future wildfire hazard as well as the exposure and vulnerability of communities and assets to future wildfire risk (Pacheco and Claro, 2020[112]). Post-fire recovery encompasses all the rehabilitation, restoration and reconstruction interventions that take place after a wildfire, including both short-term efforts to stabilise the emergency and long-term interventions aimed at the recovery of ecosystems and socio-economic assets and systems.

Emergency stabilisation

Emergency stabilisation efforts are undertaken immediately after a wildfire to contain damage and prevent cascading risks and impacts to life and ecosystems, as well as to socio-economic and cultural assets (Pacheco and Claro, 2020[112]; US Forest Service, 2021[113]). Stabilisation interventions can focus on reducing the risk and impacts of post-fire soil erosion, landslide or water contamination (UNEP, 2021[86]) as well as on restoring critical infrastructure and basic services, such as transport or electricity networks. Emergency stabilisation interventions usually focus on severely burned areas, as well as on areas considered particularly vulnerable to negative post-fire risks and impacts, such as erodible steep slopes or river catchments and critical infrastructure downstream (Cerdà and Robichaud, 2009[114]).

In many countries, emergency stabilisation is considered the key priority after a wildfire has been extinguished, as the timeliness of such interventions is critical to ensure their effectiveness. This is the case in the United States, where after a wildfire the Forest Service's Burned Area Emergency Response prioritises the stabilisation of burned lands, e.g. through the modification of drainage systems to reduce debris flow risk and the plantation of quick-growing species for hillslope stabilisation, erosion and water pollution control (OECD, forthcoming[53]; USDA, n.d.[115]). Similarly, in Chile and the United Kingdom, the treatment of burned hillslopes has been used to prevent soil erosion (Robinne et al., 2021[116]; van Hensbergen and Cedergren, 2020[5]). To contain risk, Portugal also uses fuel breaks to isolate the areas where extinguished fires could likely reignite, a practice known as rekindle control. Increased efforts in rekindle control reduced the total area burned by rekindle fires eightfold between 2001-17 and 2018-21 (from 13 000 hectares per year to 1 500 hectares per year) (ICNF, 2022[117]).

Ecological restoration

Ecological restoration measures aim to rehabilitate landscapes, natural resources and ecosystems by restoring natural biophysical processes. They can include the reforestation of burned areas, the restoration of native habitats, the treatment of invasive species, and the removal of dead biomass (Valderrama, Contreras-Reyes and Carrasco, 2018[118]). By intervening on fuel types, conditions and continuity, these interventions can significantly affect long-term landscape resilience to wildfire risk – as proven by the recent restoration of native cork oak belts in Algarve, Portugal, which contributed to reducing landscape flammability and protecting ecosystem structure and functioning (UNEP, 2022[119]). In the United States, efforts are also in place to support tree cover restoration capacity (e.g. through the Emergency Forest Restoration Program as well as seed collection and nurseries) in the aftermath of extreme wildfires (OECD, forthcoming[53]; Government of the United States, 2022[78]).

The extent to which post-fire recovery efforts are needed varies significantly. Fire-adapted ecosystems usually recover naturally following a wildfire. Yet, the growing occurrence of extreme wildfires, and most notably the outbreak of wildfires in non-fire-adapted ecosystems, hampers ecosystems' natural recovery capacity, in extreme cases leading to vegetation cover shifts (Turner et al., 2019[120]; Stevens-Rumann et al., 2018[121]) (see Chapter 2). Thus, human intervention can often help nudge the recovery process (e.g. planting trees or treating the soil) or protect ecosystems during the delicate recovery phase (e.g. against overgrazing, invasive species and deforestation) (UNEP, 2021[86]; Müller, Vilà-Vilardell and Vacik, 2020[12]). Countries such as Australia, Costa Rica and Greece have taken steps to enhance their understanding and management of post-fire ecosystem recovery needs. In Australia, after the 2019-20 extreme wildfire season, an expert panel was set up to assess wildfire impacts on native species and how to support their recovery (OECD, forthcoming[11]). After the Evia extreme wildfire in 2021, Greece took steps forward in this direction by developing the Greek Biodiversity Restoration Hub, which sets a framework for improving ecosystem recovery in burned areas through expert support, enhanced monitoring and co-ordination (OECD, forthcoming[31]; Biodiversity Recovery Hub, 2022[122]). After each wildfire, Costa Rica develops a plan for ecosystem restoration, considering both passive and active recovery options based on assessments of local ecological dynamics and conditions.

The lack of information, capacity and resources can hamper effective landscape recovery after a wildfire, often leaving ecological recovery unmanaged and unmonitored (OECD, forthcoming[31]; forthcoming[29]). This is particularly challenging on private lands, as site rehabilitation usually falls under the responsibility of the relevant landowner (Box 3.2) (OECD, forthcoming[53]). The lack of careful assessments of ecosystem recovery ability and needs can also lead to poorly adapted interventions as well as to failures to preserve ecologically functional levels of fire activity, which risks increasing wildfire risk in the long run (Schumann et al., 2020[111]). Besides, in some areas, opportunistic post-fire land grabbing poses another major challenge to effective and fire-resilient post-fire restoration (WWF, 2020[123]).

Asset recovery and reconstruction

Post-fire interventions also include measures focused on the recovery and reconstruction of damaged or lost assets and settlements. The reconstruction phase offers an opportunity to rethink and redesign the interface between human settlements and wildfire activity and to build back better, e.g. using zoning tools, fuel breaks, or building codes and standards (see Section 3.2.2). For example, in the aftermath of the extreme Camp Fire in 2018, the municipality of Paradise, United States, bought the properties located near the perimeter of the fire to turn them into fire-resilient green spaces that can act as fire breaks in the occurrence of a new wildfire (Brasuell, 2021[30]).

Major gaps remain in the development of more resilient built landscapes in the post-fire phase. Indeed, under pressure to "quickly return to normal" after a wildfire, fire-resilient land-use and building regulations often fail to be considered. For instance, in Colorado, United States, post-fire recovery efforts after the 2010 and 2012 wildfires were found to not have improved resilience to wildfires (Mockrin et al., 2016[124]). While some property owners improved building conditions and enhanced vegetation management around their properties to reduce future wildfire risk, local governments were not found to have substantially revised building and land-use standards (Mockrin et al., 2016[124]). In some cases, failure to build back better is linked to difficulties in enforcing wildfire policies at the local level (Hui et al., 2021[125]). For example, in the aftermath of the extreme Mati wildfire in Greece, local groups opposed the widening of the local street network, even though the narrow streets and absent escape routes in the WUI contributed to the high death toll (Triantis, 2022[66]). Finally, when settlement relocation is identified as the best policy option available, the socio-economic implications of such decisions also pose major challenges to their uptake. Evidence from the 2005 wildfires in the Eyre Peninsula, Australia, indicates that besides the traumatic experience of experiencing a wildfire, post-fire relocation was found to further increase the likelihood of post-traumatic stress disorder in survivors (Watts et al., 2023[126]).

3.2.4. Informing wildfire prevention: The role of wildfire risk assessment

Wildfire hazard assessment and risk information provide the foundation for all wildfire risk prevention and preparedness decisions. By providing estimates on the spatial and temporal occurrence of wildfires, risk assessments provide the critical evidence base to inform long-term risk prevention measures and interventions in the aftermath of a wildfire (Scott, Thompson and Calkin, 2013[127]; UNISDR, 2017[128]). For example, risk assessments can inform decisions on where and how to build new assets or develop certain activities (UNISDR, 2017[128]). Wildfire risk assessments consist in the identification and estimation of current and future wildfire risk by assessing potential hazard and the existing exposures and vulnerabilities that combined could generate negative impacts on people, property, services, the environment and the economy (Table 3.1) (IPCC, 2022[129]; UNISDR, 2017[128]; OECD, 2017[130]).

Table 3.1. The three steps in wildfire risk assessment

Step	What is assessed	How it is assessed
Hazard assessment	Potential for harmful wildfire occurrence and behaviour (e.g. likelihood, frequency, magnitude, spread, duration and intensity)	Gather, model and map information on fuel loads, continuity and conditions (e.g. moisture); atmospheric conditions (temperature, drought, precipitation, wind, lightning); topography; causes of ignition; assess linked hazards and potential cascading impacts
Exposure assessment	Presence of people, ecological, socio-economic assets and ecological systems in or close to wildfire-prone areas	Combine information on wildfire hazard with the spatial location of people and valued resources, activities and assets (e.g. housing, infrastructure, production capacities)
Vulnerability assessment	The characteristics of people, communities, ecosystems, assets and systems that make them prone to be adversely affected by wildfires	Susceptibility and fragility of people, ecological and socio-economic assets; capacity of humans, physical assets, and socio-economic and environmental systems to cope with and recover from wildfire events

Source: Based on JRC (2022[131]) and UNISDR (2017[128]).

Wildfire hazard modelling is the first step in wildfire risk assessment. Wildfire hazard modelling allows estimating future wildfire occurrence (i.e. likelihood and frequency) and behaviour (i.e. the way wildfires ignite and spread) (Müller, Vilà-Vilardell and Vacik, 2020[12]) based on a wide array of geophysical information including, for example, data on vegetation cover, landscape characteristics (e.g. slope, elevation), climate and weather patterns, as well as historical wildfire and weather records (Scott, Thompson and Calkin, 2013[127]; UNISDR, 2017[128]). In some cases, wildfire models also build on existing simulations of vegetation cover change and fire-atmospheric and fire-vegetation feedback interactions. All this information can be represented spatially in the form of wildfire hazard maps, which represent a key tool for grasping and communicating the spatial distribution of wildfire hazard to relevant stakeholders.

Countries widely use wildfire hazard modelling and mapping, and recent technological and scientific developments have allowed major advancements in this domain. In Austria, the current hazard models combine information on vegetation cover, topography and potential wildfire drivers (Müller, Vilà-Vilardell and Vacik, 2020[12]). In the United States, the accuracy of existing models on wildfire occurrence and spread, fire-atmospheric feedbacks, as well as smoke spread, soil heating and moisture evaporation during a wildfire has significantly improved (USDA, n.d.[132]; USGS, 2020[133]; NIST, 2021[134]). Building on wildfire hazard models, countries such as Portugal and the United States have developed national and subnational wildfire hazard maps that classify the territory by hazard level (USDA, n.a.[135]; DGT, n.a.[136]; OECD, forthcoming[53]). In Portugal, in addition to the national hazard map, each municipality is also required to have a wildfire hazard map that is updated every ten years (OECD, forthcoming[29]). In Slovenia, hazard assessments are carried out at the regional level based on the methodology prescribed by the national government (Müller, Vilà-Vilardell and Vacik, 2020[12]). Despite significant improvements, some challenges remain. Persisting gaps in data availability and quality (e.g. on fuel cover) and knowledge gaps on the complex interactions of different wildfire drivers (e.g. fire-vegetation and fire-weather feedback), along with limitations in the wildfire models' predictive capacity, limit the comprehensiveness of existing projections (OECD, forthcoming[29]; forthcoming[31]). Furthermore, increasingly sophisticated hazard models also require high-resolution, up-to-date spatial information (e.g. on available fuel and weather conditions), which can be very resource intensive.

Wildfire hazard assessments need to be integrated with spatial information on the exposure and vulnerability of human and ecological systems (Scott, Thompson and Calkin, 2013[127]). Yet, in most cases, the integration of socio-economic information into wildfire risk assessments remains a challenge due to the persisting gaps in the availability of data on wildfire exposure and the unavailability of impact assessments to estimate the vulnerability of people and assets (Jacome Felix Oom et al., 2022[131]). Wildfire risk maps exist at the national level, as well as in some states, in the United States (FEMA, n.d.[137]; Oregon Department of Forestry and US Forest Service, n.d.[138]). In Italy, some efforts have been made at the regional level to integrate data on the exposure of people and assets with hazard maps (Müller, Vilà-Vilardell and Vacik, 2020[12]). However, in most countries, risk maps are currently not available (OECD, forthcoming[31]; forthcoming[11]; forthcoming[29]). Some good practices have emerged to address these challenges. In Portugal, efforts are underway to develop a nationwide wildfire risk map, as the absence of such tool was identified as a key challenge to effective wildfire management (OECD, forthcoming[29]). In Greece, the region of Attica has carried out a comprehensive wildfire risk assessment considering hazard, vulnerability and exposure in selected high-risk areas, with projections available at the neighbourhood level (OECD, forthcoming[31]).

To effectively assess wildfire risk, it is important to account for the effects of climate change on the weather, fuel and ignition patterns that determine wildfire risk (UNISDR, 2017[22]). Climate change has already altered atmospheric temperatures, precipitation, lightning and wind patterns, the occurrence of heat and drought extremes, and changes in vegetation cover. These changes are projected to continue under future climate change, further affecting fire weather, fuel conditions and ignition likelihood (see Chapter 2). Hence, considering the impacts of future climate change in wildfire hazard models is critical (Vilar et al., 2021[139]; IPCC, 2020[140]). Yet, climate change projections often fail to be integrated into wildfire models and broader risk assessment efforts. For example, while wildfire risk projections exist in Portugal, they are not integrated into existing risk assessment and planning processes. The Portuguese Environment Agency is currently working on updating the downscaled projections of climate-induced wildfire risk and providing guidance on how to best integrate them into risk maps and other planning instruments in the National Roadmap for Adaptation 2100 (OECD, forthcoming[29]). Overall, while research on how different climate scenarios affect fire weather indices in southern Europe has significantly advanced (Camia, Liberta and San Miguel Ayanz, 2017[141]), further efforts are needed to better reflect emerging scientific insights on the links between climate change and future wildfire activity in wildfire risk assessments.

In addition to the limited consideration of climate change impacts on wildfire activity, other challenges in wildfire risk assessment remain. Limitations in the availability and quality of historical wildfire records, including inconsistencies within and across datasets, can hamper the predictive capacity of wildfire models (Filkov, Duff and Penman, 2018[142]; Artés et al., 2019[143]; Hincks et al., 2013[144]). Modelling and mapping wildfire risk at the subnational level also remains a challenge, as it requires disaggregated data as well as appropriately downscaled models – two elements that often lack (Loureiro and Barreal, 2015[145]). In countries where wildfire risk assessment is undertaken at the subnational level, such as Italy, the lack of a national standardised risk assessment methodology also poses consistency challenges (Müller, Vilà-Vilardell and Vacik, 2020[12]). Furthermore, while more advanced models have emerged that allow accounting for changing conditions in wildfire projections, these are not yet widespread in public administrations (Box 3.4) (Müller, Vilà-Vilardell and Vacik, 2020[12]). Finally, while improving scientific and technical knowledge and data availability have increased model accuracy, a level of uncertainty on existing projections remains (Scott, Thompson and Calkin, 2013[127]; PreventionWeb, n.d.[146]).

Box 3.4. Adapting wildfire hazard modelling in the context of climate change

Data on past wildfire events are key to informing and refining wildfire hazard models, as they allow to understand wildfire trends and characteristics over time in specific areas (Hincks et al., 2013[144]). Today, several countries and organisations regularly record information on past wildfire events, some of which is publicly available (Table 3.2).

Table 3.2. Examples of databases and portals on past wildfire events

Wildfire database	Geographical coverage	Type of information
European Forest Fire Information System (EFFIS)	40+ European, Middle East and North African countries	Number of fires, burned area, maps, satellite information, historical information on meteorological conditions and fire danger for individual countries, long-term weather forecasts. Data on individual fires and reports after each fire season at the country level.
United States Geological Survey (USGS) database	United States	Area burned, ignition dates, fire causes for wildfires that occurred between 1878 and 2019.
Swissfire	Switzerland	Fire outbreak, vegetation, fire causes, burned area, fire type, firefighting efforts, weather data, land use, population density.
Fire Climate Change Initiative	Global	Burned area, wildfire impacts (e.g. air quality, carbon emissions) from 1982 onwards.
Global Wildfire Information System	Global	Brings together existing information sources at national and regional levels, information on fire regimes.
Global Fire Emissions Dataset	Global	Satellite information on fire activity, vegetation productivity, monthly burned area, fire emissions.

In the context of current climate and land-use changes, past wildfire trends do not necessarily reflect future wildfire activity (Hincks et al., 2013[144]). Hence, past data alone are not sufficient to effectively assess future wildfire risk (PreventionWeb, n.d.[146]). To address these limitations, new wildfire hazard models have emerged that integrate historical wildfire records with other possible simulated events that have not occurred but could potentially occur based on the theoretical and empirical knowledge at hand. By doing so, these models (known as probabilistic models) allow accounting for changing conditions, overcoming the limitations of projections that solely rely on historical records, and eventually delivering a more comprehensive picture of all potential future wildfire events. The results of these probabilistic models are provided through different scenarios – each associated with an estimated likelihood of occurrence (PreventionWeb, n.d.[146]).

Sources: EEA (2021[147]); EFFIS (n.d.[10]); ESA (2021[148]); GFED (n.d.[149]); GWIS (n.d.[150]); PreventionWeb (n.d.[146]); SwissFire (n.d.[151]); Welty and Jeffries (2020[152]); Hincks et al. (2013[144]).

3.2.5. Building resilience to wildfires by raising awareness

A good understanding and perception of risk levels and potential exposures are essential to enable all stakeholders to take appropriate risk reduction measures to reduce or prevent their own risk and the risks that their activities could generate for others (OECD, 2016[153]; Wilson, McCaffrey and Toman, 2017[154]). Awareness-raising efforts can take many forms, including sharing risk information in ways that are easily accessible, developing education and training programmes, and sharing knowledge and information on good practices to reduce risk (OECD, 2016[153]).

Risk communication and awareness-raising activities for wildfire risk have mostly been spearheaded by civil protection agencies, fire services, meteorological institutes and local governments (OECD, forthcoming[31]; forthcoming[53]; forthcoming[29]). Particularly extreme wildfires in recent years have raised policy makers' awareness of the existing gaps in wildfire risk communication. As a result, several large-scale risk communication campaigns have been launched (Table 3.3). Portugal's Safe Village Safe People programme promotes awareness of good behaviours to reduce and prepare for wildfire risk in rural areas. In the United States, the Colorado Wildfire Risk Public Viewer portal provides easily accessible information for landowners on the wildfire risk their properties are subject to (Colorado State Forest Service, n.d.[155]). Education programmes in schools and communities have also been developed to scale up wildfire risk awareness. For instance, local schools in Jamaica have partnered with the national Fire Brigade to raise school children's awareness of wildfire risk (FEMA, 2010[156]).

Table 3.3. Examples of existing awareness campaigns

Initiative	Country	Description
Firewise	United States	Informs individuals, particularly homeowners, about wildfire risk, suggests steps to reduce wildfire risk for properties and communities, e.g. via media channels, education tools and an information website
Portugal is Calling (Portugal Chama)	Portugal	Informs private and public stakeholders on appropriate behaviour to prevent wildfires and what to do in the event of a wildfire, e.g. via billboard campaigns and media messages
Safe Village Safe People (Aldeia Segura Pessoas Seguras)	Portugal	Promotes good practices to reduce (and prepare for) wildfire risk in fire-prone areas, targeted particularly at local communities in rural and wildland-urban interface areas, e.g. via information posters and videos on self-protection measures, training programmes and information events
FIRELIFE	Hungary	Raises awareness of wildfire risk among the public (e.g. using poster and billboard campaigns and education activities in schools) and trains professionals (e.g. farmers, foresters, firefighters) on how to reduce wildfire risk

Sources: National Fire Protection Association (2021[157]); Portugal Chama (n.d.[158]); AGIF (n.d.[159]); ANEPC (2018[160]); European Commission (2019[161]).

To enhance the reach and inclusiveness of awareness-raising efforts, programmes and campaigns are increasingly well-targeted to specific audiences. Providing information in multiple languages has helped raise awareness in highly touristic areas as well as in areas characterised by a multilingual population. As perceived gender roles were also found to influence risk perception, Australia developed its Gender and Emergency Management Guidelines, which promote the use of gender-specific messaging in risk communication (Australian Government, 2016[162]; OECD, forthcoming[11]). However, further efforts are needed to raise public awareness of wildfire risk and stimulate the uptake of risk prevention measures by private stakeholders (Ganteaume et al., 2021[163]). This is particularly challenging as risk perception and engrained behaviours that can influence risk levels are difficult to shift.

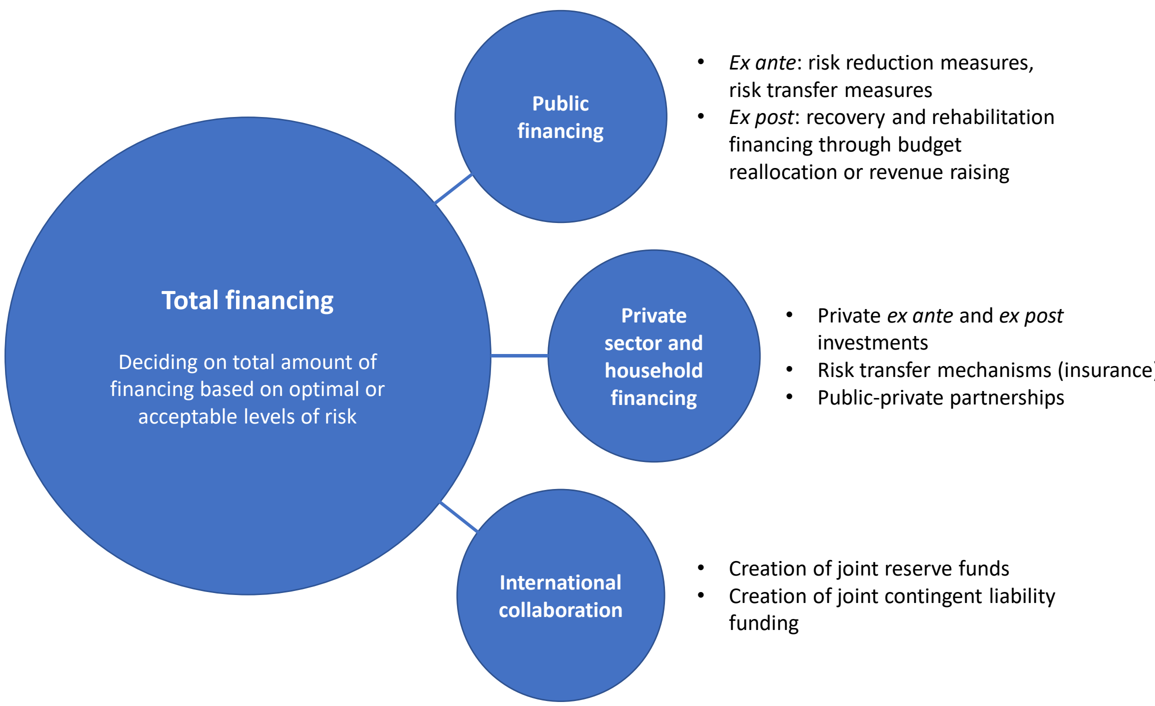
3.3. Financing wildfire risk prevention

3.3.1. Public funding for wildfire management: The need for a paradigm shift

In light of the growing wildfire risk, securing sufficient and stable funding for wildfire management is critical to build long-term resilience. To date, a large share of the funding for wildfire risk management comes from public budgets (Swiss Re, 2015[19]). While funding structures vary significantly across countries, funding for wildfire management is typically provided through a combination of local, state and national governments and agencies. For example, in the United States, the bulk of funding for wildfire management is provided by the Forest Service and the Department of the Interior and complemented by state and local budgets (OECD, forthcoming[53]; Congressional Research Service, 2021[164]).

Deciding on wildfire risk financing entails making important trade-offs. The disruptions caused by extreme wildfires have an impact on individual households, businesses and the public sector alike. Hence, all actors have to decide to which degree and how they will invest in reducing risk exposure and to which extent they choose (or are obliged to, given budget constraints) to retain risk. Governments usually face three challenges when designing their wildfire risk financing strategies. The first entails determining the overall amount of resources to be allocated to wildfire risk management and the level of risk they choose to retain. The second consists in choosing how to finance risk management. Indeed, governments have several instruments at their disposal, each of which entails different distributional effects. Finally, a third challenge lies in leveraging the participation of the private sector and individual households in financing resilience measures or investing in risk transfer arrangements, to avoid governments from having to shoulder the entire burden of disruptive shocks. Collaboration with other countries can also contribute to jointly financing risks (Figure 3.5) (OECD, 2014[165]).

Figure 3.5. A risk financing strategy mix involving public and private funding and international collaboration



Source: Adapted from OECD (2014[165]).

In response to growing wildfire occurrence and severity, many countries have scaled up existing funding for wildfire management. In the United States, the federal government nearly doubled its annual budget for wildfire management between 2011 and 2020, which reached about USD 6 billion in 2020 (Congressional Research Service, 2020[166]). Portugal has also significantly increased public funding for wildfire management, which grew by 120% between 2017 and 2021 (from EUR 143 million to EUR 316 million) (OECD, forthcoming[29]). In most cases, the increase in wildfire management funds has been financed by budget reallocations. In Australia, a large share of the funding is generated through insurance premiums. For instance, in New South Wales, a tax on insurance premiums provides almost three-quarters of the state's Fire and Rescue service, with the remainder funded by the federal, state and local governments (OECD, forthcoming[11]). Property taxes are used for similar purposes in the state of Victoria (Swiss Re, 2015[19]). Many governments also use emergency mechanisms such as contingency and reserve funds, i.e. public funds that allow governments to address exceptional emergency response costs, to fund wildfire management. The Federal Emergency Management Agency's Disaster Relief Fund in the United States and Australia's National Disaster Relief and Recovery Arrangements have allowed financing emergency response and recovery efforts, as well as providing assistance to households and businesses affected by wildfires (Richards, 2018[167]; OECD, 2015[168]) (OECD, 2015[168]). International co-operation has also contributed to scaling up funds and capacity for wildfire prevention (Box 3.5), as well as for emergency response and recovery.

Box 3.5. Scaling up wildfire risk prevention through international co-operation

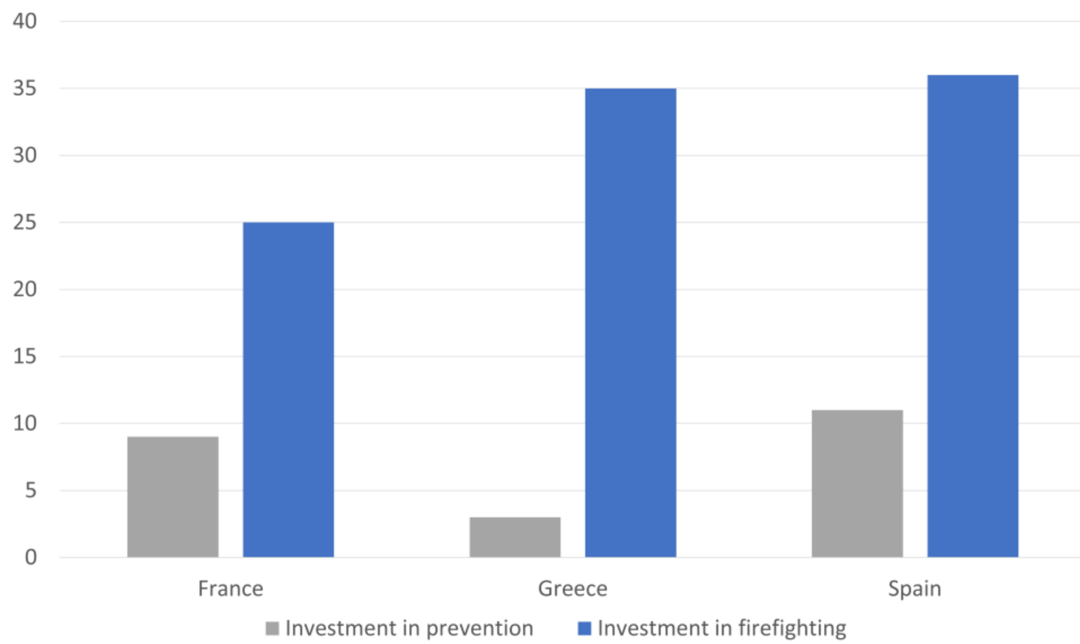
International co-operation can help ease the burden of wildfire management on individual countries' public expenditures. Successful bilateral agreements and partnerships to enhance wildfire prevention are in place between Canada and the United States as well as between Australia and New Zealand, e.g. through the Wildland Fire Management Canada-United States Program, the Trans-Tasman Fire and Emergency Management Forum, and the Australia-New Zealand Fire and Emergency Services Authorities Council. Besides, several international agreements and efforts have emerged to enhance cross-border and mutual support in wildfire risk assessment, fuel management, fire monitoring and capacity building. In Europe, the European Regional Development Fund provides funding for rural development projects, including fuel management activities. The European Union's Horizon 2020 programme provides funding for research and innovation in fuel management and other activities. In addition, the European Union has also provided funding for disaster recovery after extreme wildfire events, for example via the EU Solidarity Fund (European Commission, n.a.[169]). The EU Civil Protection Mechanism also contributes to strengthening wildfire prevention by facilitating co-operation across EU member states and eight other participating countries (European Civil Protection and Humanitarian Aid Operations, 2022[9]).

Sources: European Commission (n.a.[169]); OECD (forthcoming[53]; forthcoming[11]; forthcoming[31]; forthcoming[29]); European Civil Protection and Humanitarian Aid Operations (2022[9]).

While a strong recognition of the need to invest in wildfire risk prevention has emerged across countries, the increase in available funding to date has mostly been used to strengthen emergency response capacity. In many wildfire-prone countries, institutional frameworks and incentives remain heavily tilted towards emergency response and countries struggle to promote more prevention-oriented strategies (Drapalyuk et al., 2019[170]; OECD, forthcoming[53]; forthcoming[29]; forthcoming[31]; forthcoming[11]). Consequently, spending for wildfire suppression remains up to six times higher than the funds allocated for prevention (Figure 3.6). This structural funding imbalance has only been exacerbated by frequent "fire borrowing", i.e. the practice of diverting funds earmarked for wildfire prevention to fund emergency response and recovery. This practice, along with persisting budget constraints, has reduced the funds available for wildfire prevention measures, leading to a decline in the availability of resources for wildfire prevention and thus further exacerbating the gap between prevention and suppression funding (North et al., 2015[171]). For instance, due to a combination of budget constraints and reallocations, the funding allocated to the Greek Forest Service – the main entity responsible for wildfire prevention – shrunk by nearly 30% between 2010 and 2017, from EUR 116 million to EUR 83 million (GFMC, 2019[172]; OECD, forthcoming[31]). The growing costs of wildfire suppression in the context of climate and land-use changes further exacerbate this funding gap, raising concerns about the sustainability of public funding practices going forward (Saha et al., 2021[173]).

Figure 3.6. Public investments in prevention and suppression in France, Greece and Spain

EUR per forest hectare

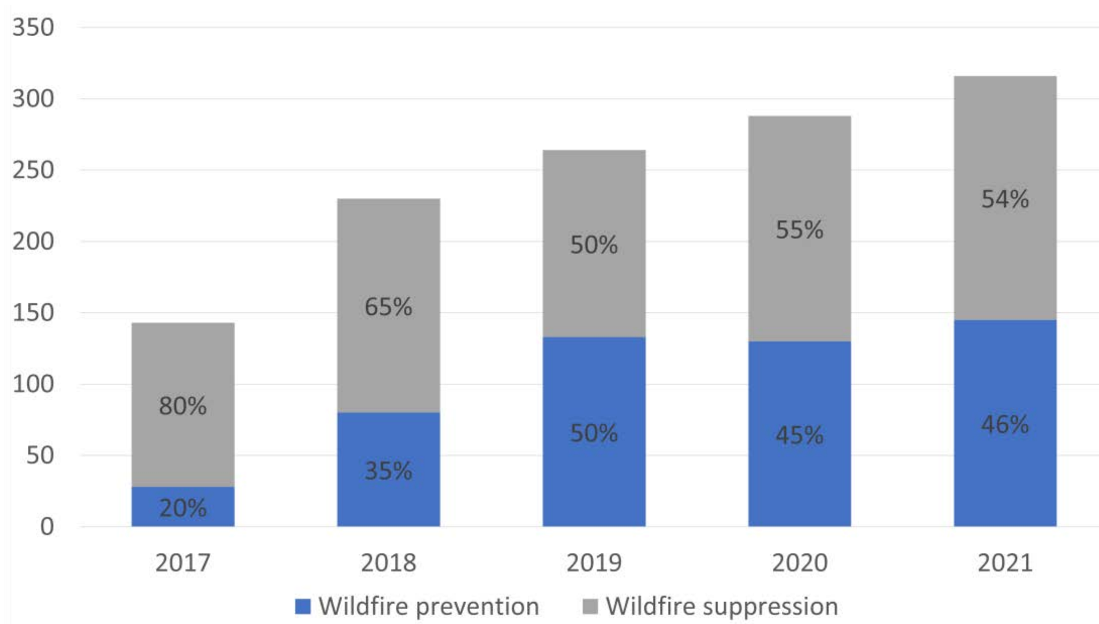


Notes: Data retrieved from WWF (2019[174]). Information on Spain is based on data from the Spanish Official School of Forestry Engineers and refers to the period 2008-17. It includes state and regional investment, as regional governments share competences in forest management. Information on France is based on data from the National Institute of Geographic and Forest Information and refers to the period 2009-18. Information on Greece is based on WWF estimations.
Source: Based on WWF (2019[174]).

Following particularly extreme wildfires in recent years, some governments have started to increase resources for wildfire prevention. In the aftermath of the 2017 wildfires, Portugal significantly boosted public funding available for wildfire prevention (Council of Ministers, Portugal, 2020[175]), bringing prevention and suppression funding to near parity. While in 2017 only 20% of wildfire management funding was allocated to prevention, by 2021 it received 46% of public funds from a greater overall budget (AGIF, 2021[176]; OECD, forthcoming[29]) (Figure 3.7). In 2022, the United States also scaled up its efforts on fuel management and prescribed fires as part of forest and landscape health management, with USD 5 billion dedicated to such measures (OECD, forthcoming[53]). Funding for wildfire prevention also increased in Greece in 2022, thanks to support from the EU Recovery and Resilience Facility, in addition to national funding efforts. As a result, EUR 72 million were allocated for the AntiNero wildfire prevention programme (Ministry of Environment and Energy, Greece, 2022[177]; OECD, forthcoming[31]). To enhance subnational governments' revenue streams to support wildfire prevention, the government of California, United States, has established a fee on properties located on state land, which is used to fund wildfire prevention in WUI areas. The government of Colorado, United States, provides application-based grants to local governments to support wildfire prevention. In 2023, these grants amounted to USD 9.5 million (Colorado State Forest Service, 2023[178]).

Figure 3.7. The shifting focus from suppression to prevention in national public funding in Portugal, 2017-21

Million EUR



Source: Based on AGIF (2021[176]).

3.3.2. The role of insurance coverage for wildfire risk

Insurance coverage for wildfire risk is important to strengthen the financial protection of private stakeholders and reduce the liability for governments that compensate for losses and damages. Insurance coverage for wildfire risk can also encourage individual wildfire risk prevention investments (OECD, 2021[179]). For example, premiums can be adjusted to reflect individual risk reduction needs, discouraging development in fire-prone lands and encouraging fire-proof development (von Peter et al., 2012[180]; Kelly et al., 2017[181]). In the United States, some insurance providers give a 5% discount on insurance premiums to homeowners that undertake certain wildfire prevention measures (Galbraith, 2017[182]). In California, the "Safer from Wildfires" programme legally mandates insurance providers to provide discounts on insurance premiums for insured individuals that undertake wildfire prevention efforts (California Department of Insurance, n.d.[183]). In some cases, insurance schemes can even require preventive measures to be adopted in order to be eligible for insurance coverage (Galbraith, 2017[182]; Chirouze et al., 2021[184]).

The extent to which insurance coverage for wildfire risk exists varies significantly across and within countries. While in some countries, such as Greece, insurance coverage for wildfire risk is part of basic property insurance coverage (OECD, forthcoming[31]), in others it remains largely unavailable in many parts of the country (OECD, forthcoming[29]). Overall, the share of wildfire losses that are insured remains relatively low across OECD countries (OECD, 2021[179]). In Greece, only around 15% of dwellings and 230 000 commercial properties have insurance coverage against wildfires (World Bank, 2021[185]), and only 9% of all wildfire losses in the country were covered by insurance between 1990 and 2019 (OECD, 2021[179]). Similarly, in Portugal, the share of wildfire losses covered by insurance was around 10% in 2021 (OECD, 2021[179]).

In some cases, the low uptake of insurance coverage for wildfire risk is also linked to the low levels of insurance availability or affordability. Increasingly extreme wildfires have posed a challenge to insurance companies' financial sustainability in some particularly fire-prone areas, leading them to pull back from the market (Golnaraghi, 2018[186]). For example, after the 2018 Camp Fire in California, insurance companies' refusal to renew insurance coverage for high-risk properties left over 340 000 properties uninsured (Moss and Burkett, 2020[187]). In other cases, growing wildfire risk has translated into unaffordable insurance premiums (California Department of Insurance, 2021[188]). The lack of affordable insurance schemes represents a major challenge to wildfire risk reduction in Portugal (OECD, forthcoming[29]) and the United States. In California, in some cases, insurance premiums rose by up to 500% after the 2018 wildfires compared to pre-fire levels (Moss and Burkett, 2020[187]).

Furthermore, underinsurance (i.e. a situation where the maximum pay-out provided by an insurance company is insufficient to cover the full costs induced by a wildfire) also remains a key challenge (GIO, 2022[189]). In Australia, the high levels of underinsurance resulted in significant financial losses for the individuals and communities affected by the extreme wildfires of 2003, 2009 and 2019-20 (Cox, n.d.[190]). For instance, the average claim for properties that were destroyed by the 2009 wildfires in the state of Victoria amounted to approximately half of the actual cost of rebuilding a house (Commonwealth of Australia, 2011[191]).

To address these challenges, some governments have developed legislation that mandates or encourages the uptake of insurance coverage against wildfires. For example, California has recently issued a mandatory one-year moratorium on the non-renewal of insurance in communities affected by wildfire (United Policyholders, 2022[192]). Yet, to date, wildfire insurance is rarely mandated by law (Swiss Re, 2015[19]).

Some governments have stepped in to address insurance viability issues for insurers in an attempt to safeguard existing wildfire insurance markets. Some Australian states have removed existing levies on insurance premiums to help contain their cost (Commonwealth of Australia, 2011[191]; Swiss Re, 2015[19]). France has set up the CatNat public-private insurance scheme to help contain insurance premiums on risks otherwise considered "uninsurable". Funding for the scheme is provided from a state-fixed rate that is added on top of all property and motor vehicle insurance, which are mandatory in France. In addition, the state provides a guarantee to back insurance providers in case of an extreme event (OECD/The World Bank, 2019[193]). Several states in the United States have set up a Fair Access to Insurance Requirements (FAIR) plan to provide insurance coverage to property owners unable to obtain insurance through the private market. In California, the FAIR plan offers broader coverage, as particularly high levels of wildfire risk have pushed a greater number of people out of the private insurance market (The California FAIR Plan, 2022[194]; OECD, forthcoming[53]). The scheme was initiated by the state, but no public money is involved; its operations are controlled and funded by insurance companies (The California FAIR Plan, 2022[194]). In Zambia, the collaboration between insurance institutions and the national bank has made possible the emergence of affordable insurance to protect private enterprises against wildfires and other climate hazards (Inclusivity Solutions, 2020[195]; Swiss Re, 2015[19]).

3.4. Towards an integrated approach to wildfire risk prevention

To enable the development and implementation of risk prevention measures throughout the policy cycle, appropriate institutional and policy arrangements are necessary. Well-designed policy and institutional frameworks enable the integration of wildfire risk prevention across all sectors and levels of government, determining a conducive environment for preventative and adaptive measures. Following particularly extreme wildfires, countries have started acknowledging the importance of adopting a whole-of-government approach in wildfire management, i.e. a collaborative approach that addresses the complex challenge of managing wildfire risk by aligning and co-ordinating the institutional interventions of wildfire management horizontally and vertically across government (McWethy et al., 2019[196]). This has occurred through reforms in both institutional and policy frameworks.

3.4.1. The institutional framework

Wildfire management usually falls under the responsibility of several actors (Table 3.4). In most countries, roles and responsibilities for wildfire management are shared between the national, state, regional and local levels.

Table 3.4. Entities responsible for wildfire management at the national level

Wildfire management role	Responsible entities
Wildfire risk assessment	Government research institutes, meteorological services, academia
Wildfire risk awareness	Ministries of Environment, civil protection agencies, meteorological services
Fuel and ecosystem management	Ministries of Environment, Ministries of Agriculture, and their subordinate agencies
Land-use planning and building regulations	Ministries of Infrastructure, Ministries of Interior, Ministries of Environment, land-use agencies
Emergency preparedness and response	Emergency management: Civil protection agencies, fire services. In some countries, forest services are also responsible for wildfire suppression
	Monitoring and early warning: Government research institutes, meteorological services
Post-fire recovery	Ecological recovery: Ministries of Environment and their relevant agencies
	Socio-economic recovery and reconstruction: Ministries of Infrastructure, Ministry of the Interior

This complex distribution of tasks and responsibilities highlights the importance of having clear roles and straightforward communication and collaboration channels across the different agencies involved in wildfire management. However, recent extreme wildfires have shed light on the faults of institutional frameworks for wildfire management. A number of independent expert committee reports after the 2017 extreme wildfires in Portugal and the 2018 Mati wildfire in Greece highlighted how unclear roles and institutional overlaps and the lack of collaboration among wildfire management agencies contributed to the devastating impacts of these wildfires (OECD, forthcoming[31]; forthcoming[29]). For example, in Greece, until recent reforms, there was no institutional collaboration mechanism between the Forest Service – the main entity responsible for wildfire prevention and the preparation of forest maps, which are key tools in wildfire suppression – and the Fire Service – the main entity responsible for wildfire suppression –, hampering a co-ordinated approach to wildfire management (OECD, forthcoming[31]).

To address the gaps and challenges unveiled by recent extreme wildfires, and with a view to enhancing integrated wildfire management, some countries have developed agencies and mechanisms to promote policy alignment and collaboration, co-ordination, and knowledge exchange across all relevant stakeholders.

Progress has been made in improving horizontal and vertical co-ordination between the public authorities involved in wildfire management thanks to the development of independent national agencies that oversee and co-ordinate wildfire policy across organisations and levels of government. For example, in the aftermath of the extreme 2017 wildfires, Portugal established the Agency for the Integrated Management of Rural Fires, a cross-governmental body under the authority of the Prime Minister that promotes collaboration, capacity and co-ordination by bringing together relevant agencies and stakeholders through cross-governmental committees and lessons learnt processes (Presidency of the Council of Ministers, Portugal, 2021[33]; OECD, forthcoming[29]). Similarly, in the United States, the creation of inter-agency task forces, such as the National Interagency Fire Center, has helped co-ordinate wildfire management efforts across states and federal agencies. In Spain, a similar system was set up to enhance co-ordination across levels of government. Costa Rica's National Commission on Forest Fires also aims to facilitate cross-agency co-operation, bringing together all relevant ministries and agencies. In Greece, a recent institutional reform integrated climate change adaptation and civil protection portfolios under the new Ministry of Climate Crisis and Civil Protection in an effort to enhance synergies across the policy cycle (OECD, forthcoming[31]). In South Africa, the Working on Fire programme has given rise to co-ordination mechanisms involving provincial wildfire protection associations and their local counterparts (UNEP, 2022[197]). In most cases, these mechanisms have proven essential to enhancing dialogue, exchange and co-ordination across public and private stakeholders, eventually reducing wildfire risk (Iseman and Miralles-Wilhelm, 2021[198]).

In parallel, a key step to facilitating cross-government collaboration has involved clarifying roles, responsibilities and cross-agency collaboration mechanisms. Some countries have developed detailed process chains to clarify roles and responsibilities throughout the wildfire management cycle, establishing clear lines of communication, developing standard operating procedures and protocols, and formalising co-operation across actors. For example, in Portugal, the creation of the National Plan for Integrated Wildland Fire Management's process chain established a clear framework for action, with key roles associated with key wildfire management steps (AGIF and IRFMS, 2020[199]; OECD, forthcoming[29]). Similarly, in Greece, the collaboration between the Forest Service and the Fire Service has also improved following a joint ministerial decision and law establishing a clear framework for collaboration (Hellenic Parliament, 2019[200]; OECD, forthcoming[31]; Hellenic Parliament, 2020[201]). Yet, despite emerging good practices, significant challenges remain in implementing an integrated approach to wildfire management, as cross-agency exchange and co-ordination remain low and fragmented in many countries. The growing risk of extreme wildfires only exacerbates these challenges, making it increasingly urgent to address them.

3.4.2. The policy framework

As wildfires cut across sectors and administrative boundaries, effective wildfire risk reduction requires the integration of wildfire risk prevention across the policy framework (Table 3.4). To enable this, some countries have developed national wildfire management strategies and plans that provide an overarching framework for the management of wildfire risk across the national territory, by promoting co-ordination and synergies across policies adopted at different levels of government. For example, in the United States, the National Cohesive Wildland Fire Management Strategy provides guidance for relevant federal agencies on both wildfire prevention and suppression measures, promoting a science-based approach to wildfire management (US Department of the Interior et al., 2001[202]). The strategy emphasises the ecological role of fire, setting out how to avoid overreliance on fire suppression and "fire exclusion" approaches, and facilitates interagency collaboration for integrated wildfire management. Similarly, in 2014, Australia released the National Bushfire Management: Policy Statement for Forests and Rangelands to guide wildfire risk prevention, response and recovery throughout the whole country (Forest Fire Management Group, 2014[203]). Portugal also recently released a National Plan for Integrated Wildland Fire Management, which establishes national policy objectives on wildfire prevention and includes a detailed process chain that clarifies procedures, roles and responsibilities throughout the wildfire management cycle (AGIF, 2020[204]; OECD, forthcoming[29]). In Costa Rica, the National Programme for Integrated Wildfire Management (Programa Nacional de Manejo del Fuego) plays a critical role in the design and implementation of co-ordinated wildfire policies across sectors. Similar efforts are also in place in Lebanon, through its National Strategy for Forest Fire Management, and Morocco, which has a Prevention and Fight against Forest Fires Master Plan (Asmar et al., 2008[205]; Ministry Delegate of the Minister of Energy, Mines, Water and Environment, Morocco, 2014[206]). Despite these emerging examples, and despite growing wildfire risk in the context of climate change in many regions of the world, most countries continue to lack overarching wildfire management strategies. In many countries, such as Italy, wildfire prevention plans only exist at the subnational level (Müller, Vilà-Vilardell and Vacik, 2020[12]).

The degree to which wildfire risk prevention efforts are integrated across all relevant government agencies can be seen in its integration into sectoral policies. Countries have mainstreamed wildfire prevention considerations into sectoral policies and strategies. Recognising the role of the forestry sector in building resilience and adapting to changing wildfire risk through forest management, countries such as Greece, Portugal and the United States have included wildfire prevention measures in forestry strategies. In Portugal, the forest strategy encourages the active management of forests to reduce wildfire risk via fuel management and highlights climate change adaptation as a key priority to tackle extreme wildfire risk (OECD, forthcoming[29]; APA, 2020[63]; Council of Ministers, Portugal, 2015[207]). In Greece, the forest strategy also calls for improved fuel management and the implementation of forest fire prevention plans to strengthen wildfire risk reduction (OECD, forthcoming[31]). A similar forest management approach is already in place in the United States, which has developed forest adaptation strategies for all its federal forests, with a focus on landscape management and capacity (Global Center on Adaptation, 2020[208]). Besides, countries such as Greece and Portugal have also integrated wildfire prevention into their biodiversity strategies, aiming to reduce the negative biodiversity impacts of extreme wildfires and recognising the role of ecosystem health in reducing wildfire risk and their impacts (Ministry of Environment, Energy and Climate Change, Greece, 2014[209]). Furthermore, Portugal's National Programme for Spatial Planning Policy recognises the importance of land-use planning in reducing wildfire risk, identifying key adaptation actions to reduce wildfire risk in rural areas (Government of Portugal, 2021[210]; OECD, forthcoming[29]). Despite these good practices, however, there is still a gap in most countries in the integration of wildfire risk reduction into sectoral strategies.

Finally, as wildfire risk grows in the context of climate change, it is important to integrate wildfire risk reduction into climate policies. Many countries reflect wildfire risk in their national climate policies. Nearly all OECD countries directly refer to wildfires as a key risk in the context of climate change in their National Adaptation Strategy or Plan. For example, France's National Adaptation Plan discusses wildfire risk as part of land-use planning, while Greece's National Climate Adaptation Strategy encourages prevention actions to integrate wildfire risk management into key sectors, such as tourism, forestry and agriculture (OECD, forthcoming[31]; Ministry of Environment, Energy and Climate Change, Greece, 2014[209]; Government of France, 2017[211]; Hellenic Republic, 2018[212]). In Portugal, one line of action of the Climate Change Adaptation Action Programme (P-3AC), i.e. National Adaptation Plan, highlights wildfire prevention as a priority focus and sets out key actions to reduce wildfire risk, including managing fuel accumulation and continuity, strengthening the economic valuation of biomass, and adapting infrastructure networks and support systems to growing wildfire risk (APA, 2019[213]). Portugal and the United States also recognise the challenge posed by extreme wildfires in their Nationally Determined Contribution under the United Nations Framework Convention on Climate Change (WWF, 2021[214]; OECD, forthcoming[29]).

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Notes

[1] While the objectives of prescribed fires and cultural fires often overlap to some extent, cultural fires form part of the intangible cultural knowledge of indigenous groups and have a traditional and cultural significance (Office of the Royal Commission into National Natural Disaster Arrangements, 2020[216]).

[2] The International Wildland-Urban Interface Code was developed by the International Code Council to support governments in enhancing wildfire resilience in WUI areas (International Code Council, 2021[215]).

Annex A. List of stakeholders

The OECD undertook interviews and exchanges with representatives from the following institutions between March 2022 and May 2023.

Table A A.1. Stakeholders interviewed in Australia

Acronym (if available)	Full name of the organisation
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DCCEEW	Department of Climate Change, Energy, the Environment and Water
NEMA	National Emergency Management Agency

Table A A.2. Stakeholders interviewed in Costa Rica

Acronym (if available)	Full name of the organisation
MINAE	Ministry of Environment and Energy *Ministerio de Ambiente y Energía*
SINAC	National System of Conservation Areas *Sistema Nacional de Áreas de Conservación*

Table A A.3. Stakeholders interviewed in Greece

Acronym (if available)	Full name of the organisation
CCISC	Bank of Greece, Climate Change Impacts Study Committee *Τράπεζα της Ελλάδος, Επιτροπής Μελέτης Επιπτώσεων της Κλιματικής Αλλαγής*
GRFU	Green Fund *Πράσινο Ταμείο*
	Hellenic Agricultural Organization, Institute of Mediterranean Forest Ecosystems "DEMETER" *Ινστιτούτο Μεσογειακών & Δασικών Οικοσυστημάτων, Ελληνικός Γεωργικός Οργανισμός «ΔΗΜΗΤΡΑ»*
HAIC	Hellenic Association of Insurance Companies *Ένωση Ασφαλιστικών Εταιριών Ελλάδος*
HFS	Hellenic Fire Service *Πυροσβεστικό Σώμα Ελλάδας*
MCCCP, GSCP	Ministry for Climate Crisis and Civil Protection, General Secretariat for Civil Protection *Υπουργείο Κλιματικής Κρίσης και Πολιτικής Προστασίας, Γενική Γραμματεία Πολιτικής Προστασίας*
MEE, GDEP	Ministry of the Environment and Energy, General Directorate for Environmental Policy *Υπουργείο Περιβάλλοντος και Ενέργειας, Γενική Διεύθυνση Περιβαλλοντικής Πολιτικής*

Acronym (if available)	Full name of the organisation
MEE, GSF	Ministry of the Environment and Energy, General Secretariat of Forests *Υπουργείο Περιβάλλοντος και Ενέργειας, Γενική Γραμματεία Δασών*
NECCA	Natural Environment and Climate Change Agency *Οργανισμός Φυσικού Περιβάλλοντος και Κλιματικής Αλλαγής*
	Region of Attica, Directorate of Civil Protection

Table A A.4. Stakeholders interviewed in Portugal

Acronym (if available)	Full name of the organisation
AGIF	Agency for the Integrated Management of Rural Fires *Agência para a Gestão Integrada de Fogos Rurais*
ANEPC	National Emergency and Civil Protection Authority *Autoridade Nacional de Emergência e Proteção Civil*
ANP	Nature Association Portugal (WWF Portugal) *Associação Natureza Portugal*
APA	Portuguese Environment Agency *Agência Portuguesa do Ambiente*
APS	Portuguese Association of Insurers *Associação Portuguesa de Seguradores*
BALADI	National Federation of Baldios *Federação Nacional dos Baldios*
CCDR-C	Regional Coordination and Development Commission - Centro *Comissão de Coordenação e Desenvolvimento Regional do Centro*
CCDR-N	Regional Coordination and Development Commission - Norte *Comissão de Coordenação e Desenvolvimento Regional do Norte*
CNADS	National Council of the Environment and Sustainable Development *Conselho Nacional do Ambiente e do Desenvolvimento Sustentável*
DGT	Directorate-General for Territorial Development *Direção-Geral do Território*
FA	Environment Fund *Fundo Ambiental*
ForestWISE	Collaborative Laboratory for Integrated Forest and Fire Management *Laboratório Colaborativo para a Gestão Integrada da Floresta e do Fogo*
GNR	National Republican Guard *Guarda Nacional Republicana*
GPP	Cabinet for Planning, Policy and General Administration (Ministry of Agriculture and Food) *Gabinete de Planeamento, Políticas e Administração Geral (Ministério da Agricultura e Alimentação)*
ICNF	Institute for Nature Conservation and Forests *Instituto da Conservação da Natureza e das Florestas*

Acronym (if available)	Full name of the organisation
	Municipality of Monchique *Município de Monchique*
SECNF	Cabinet of the Secretary of State for Nature Conservation and Forests (Ministry of the Environment and Climate Action) *Gabinete do Secretário de Estado da Conservação da Natureza e Florestas (Ministério do Ambiente e Ação Climática)*
SGAMB	General Secretariat of the Ministry of the Environment and Climate Action *Secretaria-Geral do Ministério do Ambiente e Ação Climática*

Table A A.5. Stakeholders interviewed in the United States

Acronym (if available)	Full name of the organisation
DOI	United States Department of the Interior
USDA	United States Department of Agriculture
USFS	United States Forest Service

Annex B. Questionnaire

Responses to this questionnaire informed the five case studies undertaken as part of this project.

Part I. Wildfire policy and institutional frameworks

1. The policy framework for wildfire risk governance

Q1. Does your country have a wildfire risk management strategy? If so, could you describe its main objectives and orientations, as well as its geographical and sectoral coverage? Is climate change identified as a policy priority therein? *Please specify and, if available, provide a link to the document.*

Q2. Is wildfire risk management integrated into sectoral development plans (e.g. transport, energy, health, telecommunications, agriculture, tourism, other) and strategic climate change plans (e.g. national adaptation plans, Nationally Determined Contributions)? *Please specify and, if available, provide a link to the relevant documents.*

Q3. What, in your view, are the major achievements and persisting gaps in creating a conducive, overarching policy environment for wildfire risk management? *Please specify.*

2. Key responsibilities and co-ordination mechanisms for wildfire management

Q4. Is there a central, cross-governmental agency responsible for wildfire management? When, and with what purpose in mind, was it established? What are its roles and responsibilities? *Please specify.*

Q5. What are the relevant national agencies in charge of managing wildfire risks and what are their roles, especially with regard to:

- wildfire hazard and risk assessment
- wildfire risk communication
- wildfire prevention (organisational and physical measures for risk reduction)
- wildfire risk preparedness and emergency response
- post-fire recovery, rehabilitation and reconstruction.

Please specify below.

Q6. What is the role and responsibility of subnational governments in wildfire risk management with regard to the functions detailed above? *Please specify.*

Q7. Are there any mechanisms in place to encourage and facilitate inter-agency or cross-jurisdiction collaboration or co-ordination on wildfire management (e.g. across ministries, between central and local governments, across different countries)? Can you highlight any particular achievements or existing gaps/challenges? *Please specify.*

3. Wildfire risk assessment, awareness and communication

Wildfire risk assessment

Q8. What type of information, if any, do you record on past wildfire events? If you answered yes, what type of events are recorded? To what extent is this information made public and accessible? *Please specify.*

Q9. Has climate change had a noticeable impact in driving recent extreme wildfire events? Has this attributing effect been studied and documented? *Please specify and, if available, provide a link to the relevant documents.*

Q10. Is climate change currently considered a relevant driver of wildfire risk in your country? If so, what climate-relevant information is considered in wildfire risk assessments? *Please specify.*

Q11. What is the level of availability, resolution and coverage of wildfire hazard maps? How often are they updated? To what extent do these maps integrate climate change projections? *Please specify.*

Q12. What is the level of availability, resolution and coverage of wildfire risk maps (i.e. maps including information on wildfire hazard and exposure)? How often are they updated? What are the prevailing challenges and gaps? *Please specify.*

Q13. Are projections of future wildfire risk in your country available? If so, what type of models are they based on? What is their time frame and resolution? *Please specify.*

Q14. Are expected demographic, land-use or economic development changes in wildfire-prone areas integrated into the projections of future wildfire risk in your country? If so, how? *Please specify.*

Q15. Are climate change scenarios integrated into the projections of future wildfire risk in your country? If so, how? Are there any studies on how climate change is likely to affect wildfire risk in the future? *Please specify and, if available, provide a link to the relevant resources.*

Q16. What are the tools and practices currently used to monitor real-time wildfire hazard? *Please check all that apply and specify below.*

- ☐ fire weather monitoring and forecast (e.g. precipitation, heat, wind, drought, etc.)
- ☐ fuel load and quality monitoring (e.g. vegetation mapping, fuel dryness, etc.)
- ☐ fire outbreak and propagation monitoring
- ☐ other (*please specify*).

Q17. Have wildfire risk assessment methods and practices in your country changed over the past 25-30 years to adapt to changing wildfire risk? If so, how? *Please specify.*

Q18. What are the key challenges and limitations in data availability, quantity and quality regarding wildfire hazard and risk assessment? What are the key gaps in understanding the effect of climate change on future wildfire hazard and risk? *Please specify.*

Wildfire risk awareness and communication

Q19. In your opinion, what level of awareness do different actors have regarding wildfire risk? Please check all that apply (1 = low awareness; 5 = high awareness) and add any additional details you might want to share below.

Land-use planning and management agencies	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐
Forestry agencies	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐
Civil protection agencies	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐
Subnational governments	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐
Citizens	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐
Property owners	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐
Businesses	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐
Infrastructure operators	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐

Q20. How is wildfire risk communicated to different stakeholders (e.g. government agencies across sectors and levels of governments, citizens, tourists, property owners, businesses, infrastructure operators, farmers, other) prior to wildfire events? Which tools and platforms are used? Are there any good practices you would like to share? *Please specify.*

Q21. What are the prevailing challenges and gaps in communicating and raising awareness about wildfire risk among governmental and non-governmental stakeholders? *Please specify.*

4. Wildfire risk prevention and reduction

Q22. What have been the key priorities with regard to wildfire risk prevention? Have these changed over the past 25-30 years to adapt to changing wildfire risk? If so, how? *Please specify.*

Q23. To which extent have these priorities been mainstreamed/adopted by different public sectors (e.g. transport, energy, health, telecommunications, agriculture, tourism, other)? Are there mechanisms in place to encourage their mainstreaming? Are there any good practices you would like to share? What are the prevailing challenges and gaps that need to be addressed? *Please specify and, if available, provide a link to the relevant documents.*

Q24. To what extent has the private sector adopted these priorities? What, if any, are the mechanisms in place to encourage the investment in risk prevention measures by private stakeholders (e.g. citizens, property owners, businesses, infrastructure operators, farmers, other)? *Please specify and provide examples.*

Fuel and forest management

Q25. What fuel and forest management measures and practices are in place to promote wildfire risk prevention? *Please check all that apply and specify below.*

☐ fuel breaks
☐ prescribed fires
☐ vegetation thinning
☐ forest management and restoration
☐ restoration of natural fire regimes
☐ other (*please specify*).

Q26. Have the above measures and practices in your country changed over the past 25-30 years to adapt to changing wildfire risk? If so, how? *Please specify.*

Q27. To what extent has climate change had an impact on the evolution of these measures? Do you expect it to have an impact in the future? *Please specify.*

Q28. Do these measures consider the ongoing and projected socio-economic development expected in wildfire-prone areas? How do they incorporate uncertainty? *Please specify.*

Land-use regulations

Q29. To what extent is wildfire risk considered in spatial planning and land-use decisions? What are the key measures and practices in place (e.g. banned or restricted development, zoning, buffer zones, regulated housing density, management of abandoned lands, other) to reduce wildfire risks? *Please specify.*

Q30. Have land-use measures and practices in your country changed over the past 25-30 years to adapt to changing wildfire risk? If so, how? *Please specify*.

Q31. If development is restricted in high-risk areas, is construction allowed in these areas when specific wildfire risk-reduction measures (e.g. firewalls, fireproofing of buildings, other) are put in place? *Please specify.*

Building code regulations

Q32. Are there building codes and standards in place that aim to strengthen buildings' resilience to wildfires in high-risk areas? Is their implementation binding or voluntary? What is their level of adoption and how is this monitored and enforced? *Please check all that apply and specify below.*

☐ requirements/restrictions on structural characteristics
☐ requirements/restrictions on the use of materials
☐ requirements on defensible spaces (e.g. buffer zones, fire corridors)
☐ requirements on maintenance practices
☐ requirements on reinforcement or defensive measures (e.g. fire barriers, fireproofing)
☐ other (*please specify*).

Q33. Do existing building codes and standards only apply to new development or also to existing buildings? Are there any requirements for the retrofitting of existing buildings? *Please specify.*

Q34. Are there any requirements for wildfire risk reduction specific to the infrastructure sector? If so, how are they monitored and enforced? *Please specify.*

Q35. Have building codes and regulations in your country changed over the past 25-30 years to adapt to changing wildfire risk? If so, how? *Please specify.*

Q36. Are there incentives (e.g. economic instruments, others) to encourage private actors (e.g. households, property owners, businesses, infrastructure operators, farmers, others) to invest in risk prevention and self-protection? Can you highlight any particular achievements or existing gaps/challenges? *Please specify.*

Q37. Overall, how are local and traditional knowledge, experiences and practices (e.g. indigenous practices such as traditional forestry management, etc.) for wildfire risk reduction used? Have any particularly valuable practices been identified? If so, are there any mechanisms to encourage their uptake and integration with central government interventions? *Please specify.*

Q38. Overall, are there any nature-based solutions (i.e. measures that help protect or restore ecosystems) in place to reduce wildfire risk and impacts? If so, which ones? *Please specify.*

5. Emergency preparedness and response

Q39. Are there any early warning systems for wildfires in place in your country? If so, what is their quality and level of effectiveness? What are the prevailing challenges and gaps in setting up these systems? *Please specify.*

Q40. Have wildfire preparedness practices changed over the past 25-30 years to adapt to changing wildfire risk? If so, how? How do they incorporate uncertainty and extreme fire risk into long-term management practices? *Please specify.*

Q41. Are there any experiences or good practices you would like to share with regard to emergency preparedness and response practices (e.g. firefighting operations, healthcare response, evacuation measures, etc.) in relation to climate change (e.g. wildfires becoming more extreme, etc.)? *Please specify.*

6. Post-fire recovery, rehabilitation and learning for long-term resilience

Q42. Have any studies on lessons learnt been conducted after specific extreme wildfire events? If so, how are their findings used to inform wildfire policy design and implementation? *Please specify and, if available, provide a link to the relevant documents.*

Q43. What are the three to five most significant wildfire events that have occurred in your country since 1990? Have these events affected current wildfire management practices? If so, how? *Please describe.*

Q44. What practices are in place to ensure that future wildfire hazard, as well as exposure and vulnerabilities to future wildfire events, are reduced through measures taken in the recovery and rebuilding process after a wildfire? Are there any good practices you would like to share? *Please specify and provide examples.*

7. Financing for wildfire management

Q45. Who funds public wildfire risk prevention measures at the national, sectoral and subnational levels? Have the needs for financing wildfire prevention evolved over the past decade? If so, how? *Please specify.*

Q46. In your view, are the available levels of public funding for wildfire risk management (at national, sectoral and subnational levels) appropriate? Have the levels and types of funding changed over the past decade? Can you highlight any particular achievements or existing gaps/challenges? *Please specify.*

Q47. Who funds private wildfire risk prevention measures, such as those undertaken by infrastructure operators, businesses and property owners? Are there any public subsidies available (e.g. grants, tax credits, other) to support and encourage private actors to fund wildfire risk prevention? *Please specify.*

Q48. In your view, do private actors provide sufficient funding for their self-protection? Could more be done, and how, to encourage investment in self-protection? *Please specify.*

Q49. Is any international funding (e.g. European Union, other) available for wildfire management? Has this evolved over the past decade? Does the available funding provide for wildfire risk prevention? *Please specify.*

Q50. Are there pre-arranged funding arrangements (e.g. contingency/rainy day funds) available at the national level to fund public emergency response and recovery needs across sectors and subnational levels of government? How, if at all, have these arrangements evolved over the past decade? What has worked well or less well in funding emergency response and recovery needs? *Please specify.*

Q51. Is there a public compensation mechanism that reimburses losses and damages suffered by public agencies and private actors? If so, are the rules of this mechanism outlined? Are compensation payments dependent on prior wildfire risk prevention measures? *Please specify.*

Q52. Is wildfire risk insurance (public, private or semi-private) available? If so, what impacts and costs does it cover? What has been its uptake to date (e.g. percentage of households/companies affected by a wildfire that was covered by insurance)? *Please specify.*

Q53. In your view, how could funding for wildfire management be improved? *Please specify.*

Part II. Best practices in wildfire risk prevention

Please identify, list and describe any interesting or innovative practices that you would like to highlight on specific wildfire risk reduction practices. This can include any practice related to the above themes, such as wildfire hazard and risk assessment, wildfire risk communication, financing for wildfire management, physical or organisational wildfire prevention measures, or strengthening resilience during post-fire recovery and rehabilitation. In addition, any practices that highlight how lessons learnt are incorporated into wildfire risk management reforms would be of interest. Given the focus of the OECD project, we would be particularly interested in any practices that highlight how the effects of climate change have changed wildfire practices or how existing practices have adapted to the effects of climate change on wildfire hazard/risk. This can include existing policies and practices, governance mechanisms (agencies, co-ordination mechanisms, etc.), or any relevant reforms (either proposed or implemented). Please be as comprehensive as possible in compiling this information, providing details on its benefits, the actors involved, the factors/past wildfire events that influenced its uptake, and how this practice contributes to adapting to changing wildfire risk. Please also add links to the relevant sources, where possible.

Taming Wildfires in the Context of Climate Change

This report provides a global assessment and outlook on wildfire risk in the context of climate change. It discusses the drivers behind the growing incidence of extreme wildfires and the attribution effect of climate change. It outlines the environmental, social and economic impacts of wildfires by illustrating the losses and costs observed during recent extreme wildfire events. Building on this, the report presents the findings of a cross-country comparative analysis of how countries' policies and practices have evolved in recent years in light of observed and projected changes in wildfire risk. The analysis draws on in-depth case studies conducted in Australia, Costa Rica, Greece, Portugal and the United States. The report underlines the urgent need for governments to scale up climate change adaptation efforts to limit future wildfire costs.

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