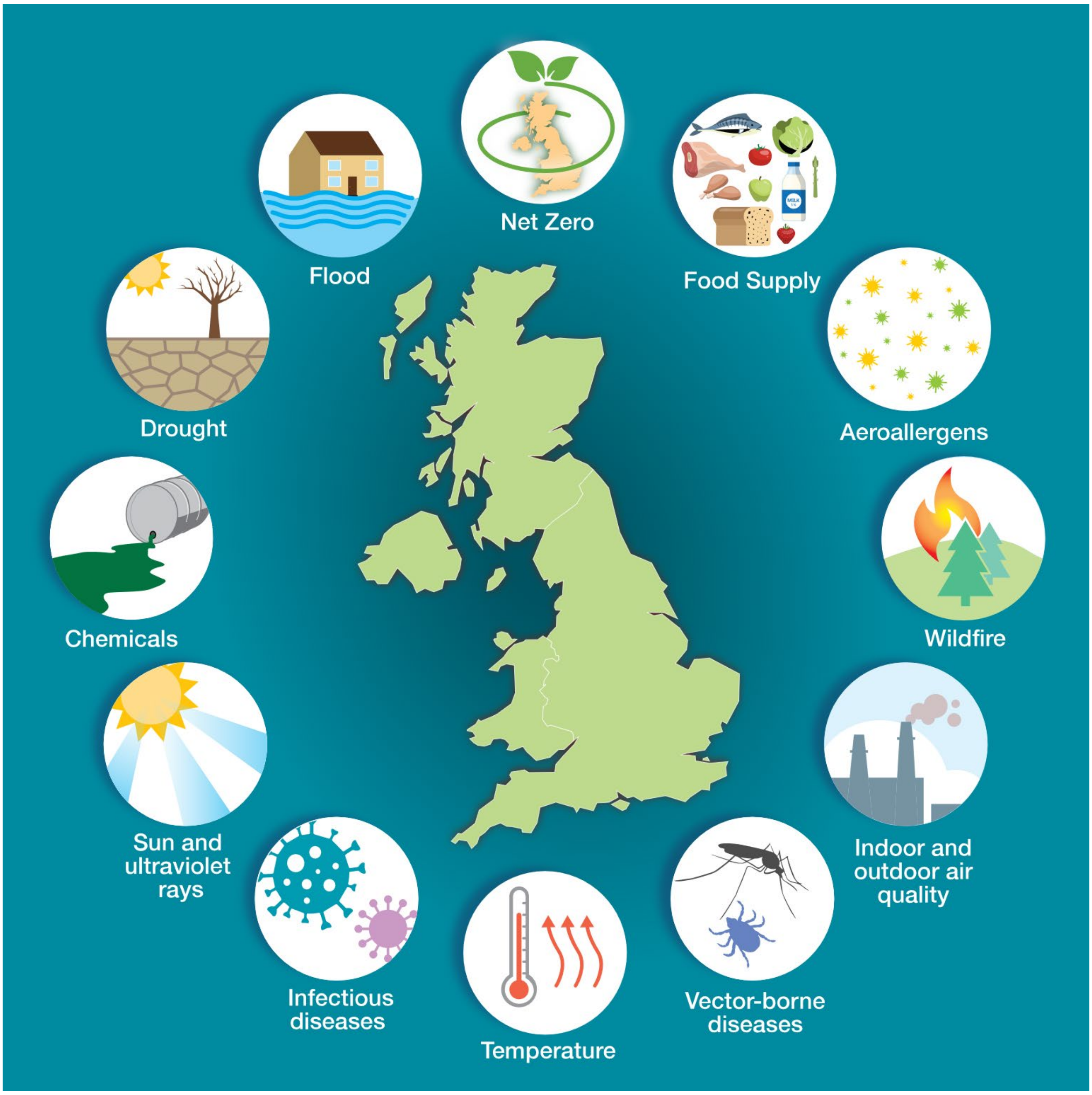
UK Health
Security
Agency

Health Effects of Climate Change (HECC) in the UK: 2023 report

Chapter 10. Wildfires and health



Summary

The evidence base on the health impacts of wildfires is improving and, as a result, this is the first time that a chapter on wildfires has been included in a ‘Health Effects of Climate Change in the UK’ report. The chapter, led by UKHSA scientists, provides an overview of wildfires within the UK, including factors that influence the occurrence and size of wildfires. Where possible, the authors use information from the UK; studies from European countries, USA, Canada and Australia are presented where there is currently a lack of evidence from the UK.

Wildfires are common in the UK, although are typically small and of short duration. There is a clear seasonality to wildfires, with grassfires occurring most commonly in the early spring (usually April). The heatwave in the summer of 2022, led to an unprecedented number of wildfires in urban locations, especially in and around London. Wildfires can lead to a range of health impacts, including injuries, respiratory and cardiovascular effects from smoke exposure, harmful mental health effects and can negatively impact health services. Wildfires can alter the properties of soil, increasing the risk of flooding and landslides and affecting water quality. Whilst there is extensive evidence of health impacts from other countries, there is relatively limited but growing evidence specific to the UK. For example, studies of the impact of the large wildfires on Saddleworth Moor (northwest England) in 2018 found that as many as 4.5 million people were exposed to poor air quality caused by smoke and estimated that this may have increased air pollution related mortality by 2 and half times.

The limited data available means that it is currently uncertain whether climate change is increasing wildfire incidence in the UK. Warmer and wetter winters can encourage plant growth and provide fuel for wildfires when plants have dried out. Warmer spring and autumn periods are likely to extend the fire season in future, and hotter and drier summers could increase the number of days with very high fire danger. In other countries, there is already evidence that climate change is increasing wildfire frequency and severity. Projections from the Met Office show that a 2°C increase in global temperatures will double the days in the UK with very high fire danger and extend the wildfire season into late summer and autumn. Other research confirms these projections, suggesting that the number of fire danger days could increase 3- to 4-fold by the 2080s. Such changes are expected to be most marked during the summer and in the South and East of England, but increases would be experienced across the UK.

The synthesis presented in this chapter highlights 2 key insights for public health. Firstly, climate change projections suggest that in future we may see conditions more favourable for wildfires. Public health guidance and climate adaptation strategies are needed to help communities prepare for, respond and recover from wildfires. Second, plans and strategies should adopt a multi-agency all-hazards approach and consider compound health impacts of wildfire events coinciding with periods of extreme hot weather, summer air pollution (ozone) events and drought.

This chapter highlights several research gaps and priorities, including the need to:

- improve understanding of how short-term and long-term exposure to wildfire smoke in the UK impacts health, including mental health and health equity
- conduct modelling of morbidity and mortality estimates of future wildfire risk in the UK under different climate change scenarios

UKHSA contributes to planning and response to wildfires in England, including providing public health risk assessments during wildfire events and supporting planning and preparedness at local, regional and national levels. UKHSA is working to strengthen the evidence base on wildfires and health in the UK by contributing to research and to the development of public facing information and messaging to raise awareness of the health risks associated with wildfires.

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Chapter 10. Wildfires and health

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Acknowledgements

The authors wish to thank Anna Stec and Robert Gazzard for their valuable reviews of the chapter. The final chapter remains the responsibility of the authors.

1. Introduction

Current climate change projections suggest that we will see conditions more favourable for wildfires with hotter and drier summers creating the ideal conditions for fire while milder and wetter winters will encourage plant growth, which can then act as a fuel for fires when conditions dry out. Projections from the Met Office show that a 2°C increase in global temperatures will double the days in the UK with very high fire danger and extend the wildfire season into late summer and autumn. It is likely that this will mean more severe and larger wildfires, many in areas that are not used to having them. This was demonstrated during the UK wide heatwave in the summer of 2022 which led to an unprecedented number of wildfires, many close to urban locations. In the future, wildfire events are likely to coincide with periods of extreme hot weather and drought, resulting in complex health challenges and seasonal surges in burden on the NHS.

This chapter is the first time that wildfires have been included in a ‘Health Effects of Climate Change in the UK (HECC)’ report. It will look at some of the main impacts that wildfires can have on public health, consider vulnerable populations, and highlight potential mitigation measures. The impacts on firefighters (occupational exposure) and the wider economic effects of wildfires are outside of the scope of this chapter. Where there is a lack of evidence for the UK, studies from other countries which experience large wildfires have been considered and their applicability to the UK is discussed.

2. Wildfires in the UK

What is a wildfire? Internationally, it is typically accepted to mean a fire, other than a prescribed fire (that is, one lit for the purposes of managing fuel or vegetation load for either ecological management or as a fire prevention measure), that occurs in a wildland (1). However, this definition can be seen as restrictive in the UK, which no longer has many true wildland areas (2) but rather a complex urban/rural landscape dominated by a range of different vegetation and land types including grassland, woodlands, heathland, forestry and peatland. Fire and Rescue Services are devolved across the UK regions and there is currently no official designation of a wildfire. A commonly used definition is ‘any uncontrolled vegetation fire which requires a decision, or action, regarding suppression’ (1). The National Fire Chiefs Council (NFCC) operational guidance for England further defines a wildfire as having to meet to one or more of the following criteria (3):

- involves a geographical area of at least one hectare (10,000 square metres)
- has a sustained flame length of more than 1.5 metres
- requires a committed resource of at least 4 fire and rescue service appliances or resources
- requires resources to be committed for at least 6 hours
- presents a serious threat to life, environment, property and infrastructure

Wildfires are surprisingly common in the UK. The UK-wide heatwave in the summer of 2022 led to an unprecedented number of wildfires in urban locations, especially in and around London (4). In England, figures collated by the Forestry Commission showed that Fire and Rescue Services attended over 360,000 wildfires over a 12 year period from 2009 to 2021, an average of 30,000 incidents per year (5), while in Wales, there were nearly 2,500 wildfires between April 2021 and March 2022 with nearly half occurring in the South Wales valleys close to people’s homes, where they can threaten property and life and produce hazardous smoke (6). The overwhelming majority of these recorded fires are very small and of short duration. But larger wildfires do occur. In 2022 983 wildfires in England and Wales met the NFCC criteria given above, while in June 2018, fires on Saddleworth Moor covered approximately 8km^2 of moorland and lasted for nearly 3 weeks. They were the largest recorded wildfires close to an urban population in the UK (7, 8).

There are several factors that influence the occurrence and size of wildfires, and these are illustrated in the fire behaviour triangle (Figure 1). Anything that burns is a fuel, and this can include both live and dead vegetation. The flammability of any fuel is determined by a range of factors including moisture, vegetation type, amount or coverage, condition and so on. Wildfires in the UK can occur in grasslands, heathland, peatland, forest and within urban areas, such as parks, gardens and verges. Typically, the dried and finer the fuel, the more flammable it is (9).

There is a clear seasonality to grassfires in the UK, with the most common period for grassfires being at the beginning of spring (usually April). Vegetation that is dead, cured from the weather, or yet to green up are conducive for fires. As grasses green up later in spring and summer, they become less flammable and the risk of fires decreases, although a long dry period in the summer can raise the risk again, especially as grasses start to die off in later summer and early autumn. The UK can also experience wildfires involving bracken, heather, gorse, moor grass, trees and peat. While peatlands usually have a very high moisture content which prevents fires, droughts or drainage can reduce the moisture content making them at risk from smouldering fires. These slow burning smouldering fires can burn for long periods and produce a relatively low buoyancy smoke which, under certain weather conditions, can accumulate close to the ground. Studies from other countries show that these types of fires can cause considerable regional air pollution events (10).

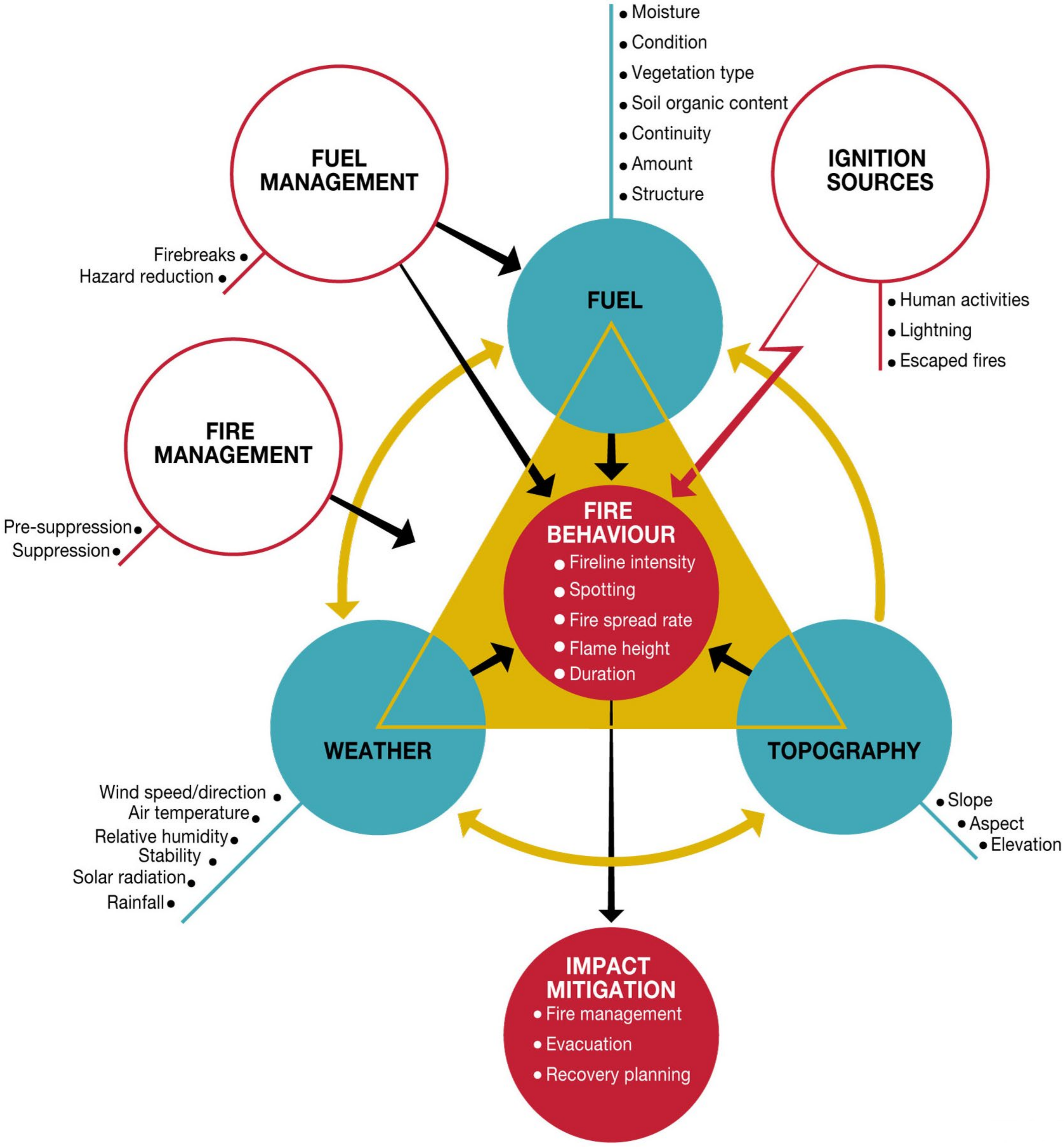
Wildfires are interdependent upon weather factors such as extreme temperatures, high winds, warming conditions, decreased rainfall, high evapotranspiration (the loss of water from evaporation from the soil surface and by transpiration from leaves), prolonged dry periods and droughts. Weather will greatly influence wildfire ignition, severity, and duration. Air and ground temperature, relative humidity, wind speed and direction and rainfall can all affect the combustibility of the fuel by altering the moisture content and the rate and spread of the fire. Hot sunny conditions will raise the temperature of the fuel and dry it out, making it more likely to ignite and spread. Strong winds can also dry out vegetation and soils, which may carry hot embers, leading to secondary fires. Wind speed and direction, rainfall and atmospheric stability will determine the direction and extent of smoke dispersion. Topography can also influence the direction and speed of the fire. Fires generally spread faster uphill than downhill due to rising hot air, and south-facing slopes will heat up or dry out quicker than slopes facing other directions.

In the UK, the Met Office's Fire Severity Index (FSI) is an assessment of how severe a fire could become if it were to start (11). It uses information such as soil moisture content, wind speed, temperature, time of year (season) and rainfall, to produce fire severity assessments which range from FS1 (low fire severity) to FS5 (exceptional fire severity). The FSI shows the current day's forecast and a forecast for the next 5 days. It does not predict the likelihood of a fire starting, but the likely severity should an ignition occur. The FSI also informs the UK Natural Hazards Partnership (NHP), which provides authoritative and consistent information on natural hazards for civil contingencies, governments and the responder community across the UK. It produces a Daily Hazard Assessment (DHA), which is an overview of potential natural hazards (including wildfires) and health implications that could affect the UK over the next 5 days. The DHA for wildfires consists of 4 colour-coded levels:

- green - elevated wildfire conditions not forecast (low risk of wildfires occurring)
- yellow - elevated wildfire conditions (likelihood of manageable wildfires) forecast
- amber - severe wildfire conditions (likelihood of difficult to control wildfires) forecast
- red - high confidence of highly disruptive wildfires

While fuel type, weather and topography will determine how a fire behaves, there needs to be a source of ignition. In the UK, the main source of ignition is thought to be through human activities such as deliberate fire setting, accidental fires due to inappropriate use of barbecues and camping equipment or from farming machinery, or existing fires such as controlled burns that get out of control. Currently there is little evidence that natural ignition due to lightning strikes is a significant issue in the UK.

Figure 1. Factors and conditions influencing wildfire occurrence.
Figure created by Andrew Sullivan for GRID-Arendal/Studio Atlantis 2021 and reproduced under the Creative Commons license CC-BY-NC-SA 3.0.



Text version of Figure 1.

Fuel, weather and topography make up the risk triangle of fire behaviour. Fire behaviour is described by fireline intensity, spotting, fire spread rate, flame height, and duration. The fire behaviour determines the impact mitigation, such as fire management, evacuation and recovery planning. Other factors influencing fire behaviour include fuel management, ignition sources and fire management.

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3. Climate change projections

Currently, UK data on wildfires is very limited and as such, it is too early to say if wildfires are increasing due to climate change. As illustrated in Figure 1, wildfires are very complex events, but weather is a key variable in wildfire frequency and severity. Current climate change projections suggest that we will see conditions becoming more favourable for wildfires in future (12). Hotter and drier summers will create ideal conditions for increased fire, whilst milder and wetter winters will encourage plant growth, which can then act as a fuel for fires when conditions dry out. Projections from the Met Office show that a 2°C increase in global temperatures will double the days in the UK with very high fire danger and extend the wildfire season into late summer and autumn (13). Other research confirms these projections with the number of fire danger days potentially increasing 3- to 4-fold by the 2080s (14). Such changes are expected to be most marked during the summer and in the South and East of England, but increases will be seen across all of the UK. Both temperature increases and changes in relative humidity are key drivers of wildfires, with decreases in relative humidity being widely recognised as a key parameter in large, severe wildfires (15). Climate change may also result in changes in vegetation type in parts of the UK which may result in increased fuel load for fires. There is already evidence from other countries that climate change is having a negative impact, with evidence that severe 2019 and 2020 bushfires in Australia were greatly exacerbated by anthropogenic climate change (16).

While such large increases in dangerous fire conditions are concerning, the actual fire risk also depends on the ignition risk, which is dependent on fuel availability and human factors. These can vary across the year and across different parts of the UK, meaning that the timing of sources of ignition may not necessarily coincide with periods of the highest fire danger (14), although the predicted hotter, drier summers may result in a change in people's recreational activities and possible more human-related ignitions. Similarly, as the UK population continues to grow, we may see increased housing developments in or near to wildfire prone areas, known as the 'Rural-Urban Interface (RUI)'. Not only could this increase the number of people at risk but also potentially increase the chances of wildfires due to accidental or deliberate fire ignitions.

It is clear that because of climate change, the UK will likely see a longer wildfire season with more late summer fires and with more areas potentially at risk. While this may not necessarily translate into more fires, it is expected that the UK will see larger, more severe and more impactful fires in the coming years.

4. Smoke composition and toxicity

The exact composition of wildfire smoke will depend on the materials fuelling the fire and the combustion conditions (whether the fire is flaming or smouldering). For example, wet vegetation burns differently to dry vegetation, while wood produces different combustion by-products than grass or peat. Fires may burn land treated with pesticides; fire suppressant foam and materials used to manage the fire can also generate potentially hazardous combustion by-products (17). This means that the composition of wildfire smoke will greatly differ from fire to fire and as such caution is needed when extrapolating data from various wildfires.

Typically, the main components of wildfire smoke are particulate matter (PM), including fine and ultra-fine particles and gases such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_X) and volatile organic compounds (VOCs) such as acrolein, formaldehyde and benzene (18, 19). However, potentially hundreds of gases and aerosols can be emitted. For example, smoke plumes from 3 wildfires in the Western USA were analysed and found to contain over 80 gases in addition to PM (20). Measured gases included CO_2, CO, methane (CH_4), hydrogen peroxide (H_2O_2), sulphur compounds including sulphur dioxide (SO_2), NO_X, chlorine compounds, polycyclic aromatic hydrocarbons (PAHs) and a large number of non-methane organic compounds including formaldehyde.

Weather and atmospheric conditions will also impact the composition of the smoke, as chemicals in the smoke may react in the atmosphere to produce other pollutants. Large wildfire events have been shown to generate secondary pollutants such as ozone (O_3), which are also hazardous to health (21). O_3 is an irritant gas and while the effects of exposure are predominantly respiratory, adverse effects on the cardiovascular system have also been reported. Elevated O_3 was detected during the 2018 Saddleworth Moor fires (8).

Wildfires are increasingly occurring near to or within urban areas. In many parts of the world, such as the USA, this is termed the wildland-urban interface (WUI) and is defined as the area where structures and other human development meet undeveloped wildland or vegetation fuels (22). However, since the UK does not have many remaining wildland areas, we have chosen to use the term rural-urban interface or RUI. Fires encroaching urban development may involve human-made structures and materials that can result in a wide variety of pollutants being present in the smoke. For example, fires involving plastic polymers such as polyvinyl chloride or polyurethane will emit considerable chlorine and nitrogen compounds including highly toxic compounds such as hydrogen chloride, hydrogen cyanide, dioxins and acrolein (22). In addition, smoke from RUI fires may also generate secondary pollutants downwind of the fire as a result of chemical reactions in the atmosphere. While there is currently limited data on the composition of RUI smoke and its likely impact on health, it is clear that emissions from these types of fires will differ significantly from wildfires and may present an additional risk to the public (23).

Many of these compounds, especially PM, NO_X, SO_2 and O_3 are common air pollutants known to cause adverse health effects in people. Evidence from many countries demonstrate that smoke from wildfires can often result in exceedances of health-based air quality standards for these compounds.

Most published research has focused on the size, composition and concentration of PM in wildfire smoke. Despite this, the relative toxicity of wildfire PM compared with PM from other sources is still poorly understood. There is some evidence to suggest that under certain conditions wildfires may produce proportionally more fine (less than 2.5µm) and ultrafine particles (less than 1µm) compared to coarse larger particles (24). This is important as particle size is a key determinant in understanding the risk to health. Particles larger than 10µm are mainly deposited in the nose or throat, whereas particles smaller than 10µm (PM_{10}) pose the greatest risk because they can be drawn deeper into the alveoli in the lungs. The strongest evidence for effects on health is associated with fine particles with an aerodynamic diameter of less than 2.5µm ($PM_{2.5}$). Exposure to $PM_{2.5}$ can cause illnesses like asthma, chronic obstructive pulmonary disease (COPD), coronary heart disease, stroke, and lung cancer and there is also evidence that links $PM_{2.5}$ to low birth weight, diabetes and diseases such as Alzheimer's and Parkinson's (25).

Several studies have suggested fine PM in wildfire smoke may contain more toxic components than ambient non-fire PM (20, 24, 26 to 33). Again, the fuel type being burnt is important. Particles collected and analysed during the 2008 California wildfires, which burnt mainly forest and brushland, were found to have high levels of organic compounds such as formaldehyde and acetaldehyde (28). Toxicity tests using mouse bioassay found that such particles contained more chemical components toxic to the lung than non-fire PM collected from ambient air from the same region (34). In Australia, frequent exposure to smoke from wildfires involving *Eucalyptus* and *Acacia* was reported to have the potential to accelerate COPD, possibly due to the presence of plant proteins or toxins (35). Wildfire smoke particles can also contain PAHs, which are compounds produced during the incomplete combustion of organic material and are known to be toxic and mutagenic. While elevated PAHs have been detected in wildfire smoke (32, 33), it is still unclear whether the type and level of PAHs are substantially different to those from other sources such as vehicle emissions and fossil fuels.

The conditions of combustion will also play an important role. Flaming conditions have been reported to produce PM with higher lung toxicity than smouldering conditions, although this was heavily influenced by the fuel type and the experimental methods employed (36 to 38). Possible mechanisms that may explain the higher toxicity include more oxidative potential due to presence of more organic compounds (39, 40) and increased respiratory infection by altering pulmonary macrophages activity (41).

In addition to PM, recent research has looked at the presence of other hazards within wildfire smoke. Advances in air quality monitoring have identified the presence of isocyanic acid in smoke plumes from wildfires at concentrations that are potentially a risk to health (42 to 44). Isocyanic acid is a highly toxic gas which can potentially contribute to the development of cardiovascular and respiratory diseases. Heavy metals have also been detected on smoke particles including copper, zinc and lead (45). Additionally, wildfire smoke may also have a biological component and may contain microbes that remain viable (46). The source of these microbes is likely to be from the soil and underlying biota. As bioaerosols are well known to cause a range of health effects in people, such as respiratory infections and allergic responses, this raises the possibility of exposure to potential hazardous microbes within the smoke.

Clearly the composition and toxicity of pollutants within wildfire smoke will vary considerably due to the fuel or vegetation being burnt. The lack of data from UK wildfires and the inconsistency in the current evidence base means that it is difficult to draw direct comparison of smoke toxicity from wildfires in other countries where the fuel type and load, combustion and weather conditions will differ significantly. Despite such uncertainties, it is clear that wildfire smoke can contain pollutants that are known to be hazardous to health.

5. Health effects

5.1 Injuries

Like any fire, wildfires can present a range of hazards that can cause injury or death, including suffocation, burns, electrocution, and injuries caused by unstable trees, buildings and electricity poles. People may be exposed to hazardous substances including from building materials such as asbestos and lead, dust, sharp objects, as well as biological materials from soiled and water damaged constituents. Data on fatalities from UK wildfires is lacking and this makes direct comparison with other countries difficult. However, in other countries, burn injuries and other acute health impacts are well documented for emergency responders (47) but less so for resident communities impacted by wildfire events. Heavy thick smoke may cause eye irritation and can substantially reduce visibility, increasing the risk of traffic accidents (48).

There are several international examples of major wildfires that have resulted in high numbers of fatalities both among responders and civilians, including the 2017 Portugal forest fires (66 fatalities) and the 2018 Mati forest fire in Greece (102 fatalities) (49). Wildfires in Australia between 1901 and 2017 killed 846 people, including 173 people during the 2009 Black Sunday fires in Victoria. Causes of death from wildfires in other countries include smoke inhalation, burns and heart attack and from road-traffic collisions on smoke affected roads. Analysis of forest fire fatalities in Southern Europe found burns and suffocation were the most common cause of death in both emergency responders and the public (446 out of 686 fatalities) (50). Research has suggested that in Australia and Southern Europe, another common cause of mortality related to wildfires is people dying whilst trapped by fire in their homes or as they try to evacuate (49).

A small study after 2 large wildfires in California during 2017 and 2018 compared wildfire burn patients with other burn patients as a control and found a worse outcome for patients sustaining burns as a result of wildfires (19% mortality compared to 9% in the control group) (51). They also found wildfire patients had a longer length of stay in healthcare facilities and were more likely to experience wound infections (51). While the exact cause of the increase in infections is unclear, the presence of high levels of microbes in the smoke is one possible option.

5.2 Smoke exposure

Globally, there are an increasing number of epidemiological studies that demonstrate clear evidence of associations between wildfire smoke and human health, although there are comparably fewer studies from the UK and northern Europe. Reported effects are consistent with reported health outcomes associated with the same type of air pollutants found in ambient air, such as $PM_{2.5}$, NO_2 and O_3, with most published research focused on exposure to PM (typically $PM_{2.5}$). Many studies suffer from common problems around estimating exposure to smoke since wildfires tend to be episodic and often relatively short-lived. They also tend to occur in more rural areas which are not covered by air monitoring networks. As a result, the type and extent of exposure to wildfire smoke can be difficult to estimate. However, even where wildfires occur in more rural areas, the smoke can travel large distances and can negatively impact air quality many miles from the fire (52, 53).

5.2.1 Respiratory effects

Epidemiological studies from several different countries have reported significant associations between wildfire smoke exposure and respiratory morbidity and mortality (54). Several studies have reported increased visits to emergency departments during wildfire events (55 to 62), while others have reported associations with respiratory hospitalisations (60, 63 to 72).

A series of large wildfires on Saddleworth Moor, England in 2018, close to the Greater Manchester urban region burnt for nearly 3 weeks. As areas of peat were burning, the fires smouldered and produced substantial amounts of smoke, which drifted over heavily populated areas. Air quality data from the Automatic Urban and Rural Network (AURN) sites coupled with satellite measurements and data collected from an aircraft flight by the Facility for Airborne Atmospheric Measurements (FAAM) showed significant negative impacts on local air quality. Ground level concentrations of $PM_{2.5}$ were 4 to 5.5 times the usual seasonal average and were, at times, twice the then World Health Organization (WHO) recommended guideline limit of 25 micrograms per cubic meter (μg/m^3) (8). Downwind of the fire, O_3 levels were also elevated suggesting that the smoke facilitated secondary O_3 production, and CO levels were also above background concentrations. Locations up to 50 miles away saw elevated levels of air pollution during the fire (7). An assessment of the health impact of this fire, the first of its kind in the UK, suggested that as many as 4.5 million people were exposed to levels of $PM_{2.5}$ that exceeded health-based guidelines for at least one day (7).

Several studies have examined the impact of $PM_{2.5}$ in wildfire smoke in Colorado, USA. One looked at the relationship between smoke exposure and cardiorespiratory effects between 2011 and 2014 (73). Using a combination of ground level air quality measurements, chemical transport models and remote sensing data, they were able to separate out fire smoke-related $PM_{2.5}$ from background ambient $PM_{2.5}$. They estimated that for every 1μg/m^3 increase in fire smoke $PM_{2.5}$, there were statistically significant increases in asthma and combined respiratory disease based on emergency department visits and hospitalisations (73). Similar associations between smoke-related $PM_{2.5}$ and visits to emergency departments for respiratory effects, especially asthma and wheeze, were also observed during a severe wildfire season in 2012 (56).

A longitudinal study of adults with severe asthma during the 2019 and 2020 Australian bushfire season reported acute and persistent symptoms (74). In this study, individuals who had enrolled in an asthma registry were asked to complete a questionnaire about symptoms, asthma attacks and quality of life during and after wildfires. Over 80% reported symptoms during wildfires and most people required an increase in their asthma medication. The number of people visiting a doctor or GP was also significantly increased. Interestingly these results were seen despite people taking mitigation measures, such as staying indoors, to reduce exposure. During wildfire periods, PM levels were reported to be regularly above health-based standards.

A meta-analysis of 20 international studies of wildfire smoke and asthma-related health outcomes found that short-term exposure to fire smoke $PM_{2.5}$ levels were positively associated with hospitalisations (relative risk (RR) 1.06, 95% confidence interval (CI): 1.02-1.09) and visits to emergency departments (RR 1.07, 95% CI: 1.04 to 1.09) (75). This association was seen for at least 3 days after exposure, and while the reported effects were higher in studies from the USA compared to Australia, the general trends were very similar. Analysis also suggested a likely positive association between exposure to smoke and use of asthma reliever medication (salbutamol) (75).

Air pollution, especially PM, is also known to increase the risk of respiratory tract infections. There have been reports of increases in hospital admissions and visits to emergency departments for acute respiratory tract infections including upper respiratory infections and pneumonia during and following wildfires (76 to 78).

5.2.2 Cardiovascular effects

The association between wildfire smoke exposure and cardiovascular effects has been well described in a number of countries through large population epidemiological studies (64, 79 to 83). However, the mechanisms for cardiovascular effects are not well understood, and some studies have not reported an association (73, 84, 85). Animal studies have established a connection between airway irritation, altered autonomic function, and changes in cardiovascular physiology following peat smoke exposure (86 to 89). A 1-hour exposure to peat smoke was reported to have the potential to produce changes in cardiovascular function that involve alterations of homeostatic mechanisms, and the exposure may increase ‘conditional susceptibility’ for adverse cardiovascular events in individuals with pre-existing cardiovascular disease (89). Volunteers exposed to short duration, high concentration wood smoke showed an increase in markers for systematic inflammation in healthy adults (90).

The effect of exposure can be delayed, with a lag of up to 3 days resulting in significant cardiovascular health effects. Jones and colleagues presented odds ratios for out-of-hospital cardiac arrest on days with heavy smoke and up to 3 days following exposure (82). There was increased risk of out-of-hospital cardiac arrest at lag days 0, 2, and 3 (odds ratio [OR], 1.56 [95% CI: 1.05 to 2.33]; OR, 1.70 [95% CI: 1.18 to 2.45]; and OR, 1.48 [95% CI: 1.02 to 2.13], respectively) (82). Another study found heart failure was associated most strongly with dense smoke at a 3-day lag among adults older than 65 years of age (RR, 1.22 [1.10, 1.35]) but was elevated across all lags (81). Another study found an increase of 9.04µg/m^3 in $PM_{2.5}$ over a 2-day moving average (lag 0 to 1) was associated with a 6.98% (95% CI 1.03% to 13.29%) increase in risk of out-of-hospital cardiac arrests, with strong association shown by men and by older adults (80).

A study of native people in Alaska identified notable disparities in risk following exposure to wildfire smoke (83). There were increases in emergency department visits for arrhythmia, heart failure, and 'all cardiovascular' causes among this population during wildfire events (83). Such effects are likely influenced by underlying disparities in heart disease in this population, as heart disease mortality rates among Alaskan Indigenous peoples are 1.6 times the rate of the non-Indigenous Alaskan population (83).

5.2.3 Mortality

Several large-scale studies have started to link exposure to wildfire smoke and increases in mortality. Again, this is consistent with published epidemiological studies on the mortality burden due to exposure to $PM_{2.5}$ in ambient urban air. For example, a study of the impact of the Saddleworth Moor fire in northern England in June 2018 found that exposure to fire smoke $PM_{2.5}$ may have increased excess mortality by 165%, with a mean excess mortality of approximately 3.5 deaths per day (7).

A study of air pollution events and mortality in Sydney, Australia between 1997 and 2004 found that smoke events were associated with a 5% increase in non-accidental mortality, with temperature also being a key factor (91). Similarly, a study of a concurrent heatwave and wildfires in Moscow in 2010 reported a clear association between exposure to temperature, PM_{10} in smoke and excess deaths (92). The authors estimate that the combination of high temperatures and air pollution from wildfires contributed to more than 2000 deaths with the risks highest in the elderly and very young (92). Linares and colleagues analysed daily mortality in Madrid during wildfire and Saharan dust events among the general population and those over 75 years and found a reduction in the age of people dying on days with wildfire smoke (93).

A recent time series analysis of wildfires in 43 countries and regions during 2000 to 2016 calculated that for every 10μg/m^3 increase in wildfire smoke $PM_{2.5}$, the pooled RR was 1.019 (95% CI: 1.016 to 1.022) for all-cause mortality, 1.017 (95% CI: 1.012 to 1.021) for cardiovascular mortality, and 1.019 (95% CI: 1.013 to 1.025) for respiratory mortality (94). Furthermore, the study estimated that 0.62% (95% CI: 0.48 to 0.75) of all-cause deaths, 0.55% (95% CI: 0.43 to 0.67) of cardiovascular deaths, and 0.64% (95% CI: 0.50 to 0.78) of respiratory deaths were annually attributable to the acute impacts of wildfire-related $PM_{2.5}$ exposure during the study period (94). While this study highlights the global risk from wildfire smoke, it should be noted that these results may not be directly applicable to all countries due to differences in population demographics (the study looked primarily at urban populations), smoke composition and the confounding effect of other air pollutants.

Long-term exposure to wildfire smoke has also been associated with cancer mortality. Analysis of national cancer records from 2010 to 2016 in Brazil suggested that the risk attributed to wildfire smoke $PM_{2.5}$ was higher than the risk from non-fire $PM_{2.5}$ (95). However, the authors acknowledged that exposure misclassification due to population movement and exposure to other pollutants may have led to bias in the risk estimates (95).

5.3 Co-exposures

The effect of co-exposures to other pollutants or environmental factors such as heat, O_3, dust, and pollen is significant. Ozone is a potent respiratory irritant and O_3 episodes can occur during warm summer months, potentially at the same time as wildfires. Furthermore, wildfire smoke can contain pollutants that are the precursors to O_3 formation (21). Reid and colleagues looked at the impact of both wildfire $PM_{2.5}$ and O_3 on people's health following a wildfire in California, USA in 2008 (96). Using computer models, they were able to estimate exposure to both $PM_{2.5}$ and O_3 and found significant associations between each pollutant separately and respiratory effects (96). Wildfire-associated O_3 was also associated with USA emergency department visits in children with asthma (61). While reported health effects are most pronounced for $PM_{2.5}$, these studies show the impact of co-exposures to different pollutants in the smoke plume. Ozone formation is complex and O_3 precursors in wildfire smoke may be transported great distances, meaning that communities remote from the fire may be subsequently exposed to elevated levels of O_3.

Pollen can also cause respiratory problems including exacerbation of asthma (see Chapter 6) and people may be exposed to both pollen and wildfire smoke, especially during the summer. A study in Nevada, USA found that reported effects from smoke-related $PM_{2.5}$ remained once pollen exposure had been controlled for (65).

As future projections suggest the wildfire season in the UK will extend into late summer, there is the potential for wildfire smoke exposure to occur during periods of other extreme weather events such as drought and high temperatures. While a number of studies have suggested that high temperature may exacerbate the effects of PM exposure (97 to 99), the exact mechanism remains unclear. However, heat stress during wildfires will undoubtedly adversely impact people's breathing, which may increase the impact of $PM_{2.5}$ (100). During fires, people are advised to stay indoors and keep doors and windows closed to avoid smoke exposure, but hot weather may prevent people from doing so. The effectiveness of remaining indoors during wildfire events has also been examined, with the level of protection found to be dependent on a range of variables including housing age and type, and ventilation (101).

Smoke from Portuguese wildfires in October 2017 was transported into other western European countries due to the actions of a strong tropical storm (53). This storm also brought up Saharan dust from Africa which, together with the smoke, contributed to poor air quality in several countries including Portugal, Spain, France and the UK (53). It was estimated that the UK population were exposed to an additional 11.7µg/m^3 of PM_{10} on average during 7 smoky days (combination of smoke and Saharan dust) (53).

5.4 Mental health and community resilience

5.4.1 Mental health

There is clear evidence from other countries linking wildfire exposure and negative impacts on both acute and chronic mental health conditions. The conditions considered in the literature range from post-traumatic stress disorder (PTSD), anxiety, suicide, depression to more generalised mental and emotional wellbeing and feelings of stress, fear, and uncertainty both during and after fire-related disasters (102 to 108). In all cases, the rates of mental health conditions were elevated post-fire when compared to pre-event and the general population. Prevalence rates at least 1-month post-incident are, on average, 17.8% higher for generalised anxiety disorder (GAD), 19.3% higher for major depressive disorder and 11.3% higher for PTSD relative to pre-incidence prevalence (102, 105, 109 to 111). Factors which increase the risk of adverse effects on mental health included younger age, gender, lower educational attainment, low socioeconomic status, residing in a rural location, first responders, financial instability or poverty, and having pre-existing physical or mental health condition(106, 107, 109, 112). Wildland firefighters have been identified as a particularly at-risk group for increased suicide risk (108). A potential explanatory factor for the observed increased risk is what the authors describe as ‘thwarted belongingness’, reflecting an isolation from others, particularly family and friends.

A key theme in the literature is the concept of ‘solastalgia’, defined as “the distress that is produced by environmental change impacting on people while they are directly connected to their home environment” (113). This feeling of a ‘loss of place’, the community disconnect it can create, and stressors such as isolation, watching a home burn, fear and uncertainty all contribute to increased rates of adverse mental health effects (103, 105, 107, 114 to 116).

Secondary risk factors associated with the impact of the wildfire itself can also be detrimental to mental health. For instance, the magnitude of such an event, the loss of personal belongings or homes, exposure to or the fear of injury or death of loved ones and a feeling of lack of support from family, friends or the government (107, 117, 118). Such risk factors, together with the severity and level of exposure to a wildfire event, can have a considerable negative impact on mental health outcomes (119).

Some studies also considered the secondary impact of negative mental health outcomes following wildfire exposure on harmful alcohol consumption and drug misuse behaviours. The evidence demonstrates an increase in these comorbidities associated with increased prevalence of mental health conditions (102, 105, 107, 110, 117, 120). One study found a 2-fold greater likelihood of suffering from drug use or alcohol dependence 6 months after a wildfire incident among those suffering with depression (110).

Sleep disruption was another detrimental outcome on populations caused by wildfire exposure (106, 107, 121). Sleep problems such as disturbance and insomnia were associated with an increased odds of negative mental health outcomes particularly in those directly affected by a fire.

There is also increasing evidence that poor air quality in urban areas may be associated with mental health problems, especially exposure to $PM_{2.5}$ and NO_2 (122, 123). This may be due to inflammatory responses following exposure to high levels of pollution. The understanding of the mental health impacts of exposure to wildfire smoke is in its infancy and current evidence is inconsistent and limited (124).

Most of the evidence and literature has followed large wildfire incidents and comes from countries where large, severe wildfires are more frequent. However, the UK can learn from the experiences, outcomes and recommendations of other nations in light of the potential for increasing UK risk of local wildfires and their impacts, particularly mitigating mental health risks. One study recommends that wildfire risk in UK should be considered in a matter analogous to flood risk management which highlights parallels in planning and management that can be drawn and implemented from existing knowledge (125).

5.4.2 Community resilience

The importance of community resilience in mitigating negative mental health outcomes is increasingly recognised. Emotional and social support from friends and family may be a protective factor for adverse mental health outcomes and increase resilience (103, 110, 117). However, resilience can be affected by a lack of support and service provision, community and family separation and solastalgia (102, 104, 114, 115).

Community engagement and cohesion are important in building resilience and ensuring people are prepared to respond and recover from a wildfire incident. Mental health and wellbeing outcomes can be more positive where communities are involved in the planning stages in wildfire risk areas, engaged and communicated with throughout, and banded together post-event (115, 126). There is a need for interventions to support and encourage communication and community cohesion to enable collective action that will support individuals, whilst having a wider public benefit (116, 125). These must also be culturally acceptable and sustainable, whilst being accessible to all, by being embedded within communities, with targeted actions on those demographics at high risk (104, 105, 115, 116).

Many countries with wildfire problems have started to develop and use community wildfire protection plans to engage with the public, landowners and local government to enhance community preparedness to wildfires. The plans are typically designed to identify and mitigate the main wildfire hazards to both communities and infrastructure and make recommendations to reduce the impact of fire. Recommendations can include measures to reduce fuel loads and create more resilient landscapes through habitat management, improve education and awareness of the risks from wildfires. A good example of the City of Corona Community Wildfire Protection Plan which, in addition to a written plan, has created an online resource (a story map) to help disseminate information to the public in a clear and accessible fashion (127). In the

UK, a Wildfire Strategy and Action Plan will be published in 2024 as part of the third National Adaptation Programme (2023 to 2028) to reduce the risk of wildfires impacting on social, economic and environmental assets (128).

A number of initiatives have started to work with communities on wildfires, such as The Healthy Hillsides project, which is a Welsh Government-funded partnership programme to reduce the impact of wildfires across the South Wales Valleys (129). This is a collaborative project, bringing together Natural Resources Wales with the South Wales Fire and Rescue Service, Rhondda Cynon Taff and the Wildlife Trust for South and West Wales. Engagement with communities and decision-makers is a key area, and the project will undertake a health impact assessment to help improve community resilience to wildfires. More details on such initiatives are in section 7.3.

5.5 Impact on health services

Clearly a large, prolonged wildfire could have considerable adverse impacts on health services and demand, both during and after the event. This could include increased attendance at hospital or GP surgeries for health problems leading to an additional demand on health care, increased use of medication, and potential increased burdens on mental health services. Such impacts may require additional services and interventions to help mitigate and support these affected people. For example, a number of studies have highlighted the need for agile and responsive mental health services (104, 105, 115, 120, 130). Services need to be co-ordinated, planned, and prepared should a wildfire incident occur to best serve the affected population (104). Due to the surge in demand during wildfire incidents, utilising community figures to support health services and delivery in population settings, with flexibility to access, is suggested and in turn proposed to increase community resilience (104, 114, 130). It is important to ensure that at-risk groups such as those with pre-existing health conditions and those in more rural areas where access is limited are considered. It is also important to recognise that physical and mental health problems after a wildfire are often long-term with studies showing increased demand on mental health services at least 2 years post-wildfire events (107, 120, 130, 131). Therefore, the potential increased requirement for services must be planned and prepared for adequately so the UK can respond and protect public health as more wildfires occur.

5.6 Other impacts

The long-term impacts of exposure to wildfire smoke are poorly understood due to the episodic nature of the fires. A study of a cohort of outdoor housed rhesus macaque monkeys that were exposed as infants to smoke from wildfires in North California noted a number of immune and respiratory effects in later life (132). Adult monkeys exposed at the same time did not show the same persistent effects (132). However, as the study was not able to assess the infant monkeys immediately after exposure, it is possible that these effects may already have been detectable at infancy.

While it is well established that exposure to ambient air pollution, including $PM_{2.5}$, is known to increase the risk of developing acute respiratory infections, the evidence for such an effect during and following wildfires is currently inconsistent. Evidence is strongest for acute bronchitis and pneumonia, with several studies reporting high rates of emergency department visits and/or hospitalisations during wildfires (133 to 136) although several other studies have not reported similar results (57, 137).

Wildfires can also adversely impact people's access to healthcare for other needs. A study during the Australian bushfire season found a 15% reduction in patients attending hospital appointments for cardiology services (138). Similarly, Bell and colleagues reviewed the literature on health outcomes for older adults with a chronic disease and access to health care during and after climate-related disasters including wildfires (139). They found dialysis and diabetic patients were most impacted.

Several studies have quantified the health burden of wildfire smoke exposure, both in terms of population impacts and economic cost. In Canada, wildfire season (May to September) between 2013 to 2015 and 2017 and 2018 were estimated to have caused between 54 and 240 premature mortalities due to short-term exposure, and 570 to 2500 premature mortalities due to long-term exposure to wildfire $PM_{2.5}$ (140). The economic impact of these and non-fatal health outcomes was estimated to be between $410 million and $1.8 billion (acute outcomes) and between $4.8 billion and $19 billion (chronic outcomes), with the economic values comparable to the estimated health impacts following exposure to petrol and diesel car emissions in Canada (140). The economic cost of the 2018 Saddleworth Moor fires on mortality was estimated to be in the region of £21 million (7).

Finally, people may be exposed to a range of hazards post-fire especially during clean-up. Hazards may include exposure to ash and hazardous chemicals within the home or other structures, damage to buildings, trees, and infrastructure, and electrical dangers.

5.7 Soil quality and stability

Wildfires can have detrimental impacts on soils including changes in soil chemistry and deposition or mobilisation of potentially toxic chemicals. Many pollutants can be absorbed onto soil surfaces and associated organic material. For example, PAHs are produced through incomplete combustion of biomass and can be ubiquitous in the environment following wildfires (141). Samples taken from soils following wildfires in Spain identified increased concentrations of PAHs compared to unburnt soils (142).

Fires can also release metals and metalloids that are present in plants and soils, either from natural or anthropogenic sources. A comprehensive review of global wildfire data showed increased soil concentrations following wildfires for several toxic metals and metalloids including arsenic, cadmium, manganese, nickel and zinc (143). In some cases, soil concentrations increased by as much as 74%, and were most apparent following severe fires where higher rates of combustion resulted in heating of soil to depths up to 30cm (143). Such impacts were most significant on former industrial land such as mining sites, where some pollutant concentrations exceeded health-based guidelines (143). A field study at a former gold mining site in Australia demonstrated similar patterns in metal concentrations from controlled burning, suggesting this too can have detrimental impact on soil quality (144). Other studies have also noted increased concentrations of certain toxic metals where man-made structures and treated timber materials were involved in the fire (145). Data collected from the Saddleworth Moor fire in 2018 noted increased metals in burnt soils and highlighted the potential to impact local water courses via run-off (146). However, the results for this site suggested lower impacts in water than recorded for other wildfires possibly reflecting site specific factors.

Changes to soil properties from wildfires are also reported to result in increased mobility of metals, which combined with volatilisation of mercury and low molecular weight PAHs and to some extent lead, can result in impacts beyond the burn site. Wildfires may also reduce the levels of some chemicals in soils following combustion because of losses due to volatilisation and smoke generation. Studies on volatilisation suggest between 10% to 95% of the total mercury in soil and plant matter can be volatilised from a site depending upon the burn temperatures. This mercury can then be transported and deposited well beyond the burn site (143, 147). Evidence also suggests that deposition on wetlands can lead to formation of methyl mercury, which is extremely toxic to humans (143). Such increased mobility is particularly important in terms of impacts to water courses and is discussed in section 5.9.

In addition to the effects described above, combustion and heating from wildfires can modify chemical compounds and elements. For example, temperatures typically found in wildfires can enhance the oxidation of chromium from its trivalent form to the more toxic, hexavalent chromium, a known human carcinogen (148).

The presence of such pollutants in soil can present a potential risk to health. Studies have noted that metals and PAHs in soils following wildfires posed a risk to orchard workers due to a combination of pollutant enrichment and physical changes in the soil, resulting in higher levels of dust generation (145). As such it would appear logical to assume similar, and possibly greater exposure risks for any residents living on affected land. Furthermore, it is widely reported that physico-chemical changes to soil from heating and combustion due to wildfires increases the bioavailability of metals (that is, their ability to be taken up by plants and animals), suggesting that they could accumulate both in crops grown on burnt land and in livestock grazing on such sites (143). This in turn provides the potential for toxic chemicals to enter the food-chain.

In addition to natural soil chemicals and products of combustion, wildfires may also impact soil due to the chemicals used during firefighting, such as poly-brominated and fluorinated chemicals (poly-brominated diphenyl ethers (PBDEs), organophosphorus flame retardants (PFRs) and perfluoroalkyl substances (PFAS)). Tests following a wildfire in Spain were, however, inconclusive with the chemicals being found in both burnt and unburnt soils and more likely to be representative of their ubiquity and persistence in the environment (142).

Wildfires, therefore, can have impacts on both the chemistry and physical quality of soils. Increased soil concentrations and mobility of potentially harmful chemicals can pose potential risks both within burnt soils and within environments beyond directly impacted areas. Chemical changes from combustion and changes to soil properties can also lead to formation of more toxic forms of some metals. Likewise changes to physical soil properties can lead to potential hazards from instability, erosion, landslide, and flooding. While the extent of risks will vary depending upon a range of site and incident specific factors, it is important to consider these issues and raise awareness amongst populations and response agencies when planning and implementing recovery procedures after a wildfire event.

5.8 Floods and landslides

As well as impacting soil chemistry, wildfires can also alter the geotechnical properties of soils, with the potential for increased erosion and higher run-off due to changes in organic content, pH, hydrophobicity and particle size. These can lead to instability and increased potential for flooding and landslides (149, 150).

Studies of root density in burnt and unburnt soils concluded that severe wildfires can increase the risk of instability for up to 15 years after the event (151). Likewise, studies following wildfires in California indicated up to 2-fold increases of sediment run-off compared to unburnt land over a 12-month period before stabilising (152). This study also found that remedial activities such as salvage logging and top-soiling reduced run-off, although the opposite effect was also noted on other sites.

Landslides can be physically harmful to populations in the area affected but can also have wider effects such as impacts upon critical infrastructure, essential services and longer-term disturbance and changes to the land. While it may be perceived that such events are more likely to affect sparsely populated areas, this is not necessarily the case. For example, a study in the Hindu Kush Himalaya region identified over half of the population living in areas of high multi-hazard risk (153). Similarly, studies in Chile following megafires in 2017 identified 37 communities at risk from landslides and flooding with 11 of these at severe risk after the event (154). In Wales during 2020, there were a series of landslides following heavy rainfall due to Storm Dennis, with one landslide in Tylorstown, South Wales occurring on a hillside that had been eroded by recent wildfires (155).

Wildfires followed by severe rainfall may significantly intensify the effects of flooding by increased flash flooding, runoff, and erosion. Wildfire-related floods have been widely reported especially in the USA (156, 157). Compound events in which 2 concurrent or consecutive events lead to extreme societal impacts are becoming increasingly important and have notable impacts on threatened communities (158). Modelling of post fire conditions in parts of Colorado, USA suggest that erosion from wildfires could increase the chance of significant 1-in-100 year flooding events (159). The health impacts of flooding are discussed in Chapter 3.

5.9 Water quality

As discussed above, wildfires can impact both the chemistry and physical quality of soils and increase soil concentrations and mobility of potentially harmful chemicals. These changes can also have detrimental effects of downstream water quality and availability (160). Rainfall and extreme weather events can further enhance contamination and contaminant mobility as water travels faster on burnt, bare unstable ground and can enter and contaminate watercourses (143, 161). This can lead to sudden changes in water quantity and quality in streams, rivers and lakes downstream of burnt areas. During extreme rainfall events, massive sediment influx can lead to decreases in light and dissolved oxygen in aquatic systems and water courses. This can severely reduce the quality of water and cause an imbalance in water nutrient concentration and temperature (162 to 164). In addition, the increase in post-fire erosion rate by rainfall runoff and strong winds can facilitate the rapid transport of such metals downstream (161).

Water remains the main fire-fighting suppression method to completely extinguish such fires and is usually sourced from tanks and pump supplies from emergency fire vehicles, continuous supplies from fire hydrants, or open water sources such as rivers, lakes, canals or ponds. The large water quantities used to fight the fire can mix with combustion products and other contaminants in the fire water runoff. While some of this water will evaporate, large quantities can be released into local drainage networks, surface and ground waters, local aquifers and aquatic ecosystems, or during precipitation events after a wildfire. Where runoff from fires enters water catchment areas, there is a risk to health if the water is abstracted for human consumption and use, especially if robust mitigation measures are not in place to prevent contamination (165).

There is considerable evidence showing impacts on water quality during and after wildfires (164 to 176) although the scale of the impact is very site-specific. Water quality monitoring in several large river systems following the 2016 large wildfire at Fort McMurray, Western Canada found distinct, precipitation-associated signatures of ash transport in large river systems, which were not evident in nearby unburned regions (170). Suspended sediment, nutrients (nitrogen and phosphorus) and metals (lead and others) from impacted rivers were as much as 10 times greater than from those rivers from unburned regions (170).

Soil and vegetation may contain accumulations of heavy metals or organic pollutants from historic or current industrial processes, whilst fertilisers and pesticides are widely used in agriculture and forestry. There is evidence that wildfires can facilitate such compounds to leach into water catchment areas (165, 171, 172). In October 2017, following a series of rural fires that occurred in Portugal’s Central Region, monitoring of 5 water catchment areas showed a deterioration in water quality, with increased turbidity and levels of aluminium, iron, manganese and arsenic (173). Studies of another large wildfire in Central Portugal found evidence of PAHs in groundwater and surface water (174, 175). Water samples from burnt and unburnt areas were collected in 8 locations over a 19-month post-fire period and a range of PAHs were found, including naphthalene and benzo(ghi)perylene, and PAH levels increased after intense winter and spring rain events. Groundwater samples from burned areas also showed increased levels of sulphate, fluoride and nitrogen.

Analysis of ash and surface water samples after wildfires in 4 different geographical locations in the North America (California, Colorado, Kansas and Alberta) found a range of benzene polycarboxylic acids, suggesting that ash from wildfires contributes to the formation of a variety of aromatic carboxylic acids in water run-off, which may affect general water quality of watercourses (177). Pennino and colleagues evaluated concentrations and exceedances of regulatory standards for a range of contaminants in public drinking water systems in the United States (176). They found exceedances of nitrate standards in surface water and groundwater sourced for drinking water located downstream from post wildfire events (176).

Suspended solids containing elevated mercury can impact streams and water courses near wildfire sites and there are reports of fish living in affected water bodies having mercury levels above WHO guidelines for consumption (148).

There is also evidence that pollution from wildfires can adversely impact the water treatment process and increase the potential to form undesirable by-products of water disinfection (166, 167). Monitoring of stream water from 8 burned catchments within the Hayman fire, Colorado, USA found elevated levels of disinfection by-products including trihalomethanes and chloral hydrate (166). These catchments supplied drinking water to over half million people in Denver.

The Tubbs wildfire in Santa Rosa, California destroyed critical infrastructure controlling and maintaining the water distribution network (165). After extensive odour complaints in the drinking water supply a month later, monitoring found benzene and toluene concentrations above state and Federal government guidelines. A ‘do not drink’ and ‘do not boil’ notice was issued, and over 175,000 people were provided with alternative supplies for nearly 12 months. The cost to repair and remediate the supply was put at nearly $8 million (165). ‘Do not drink’ notices were also issued following the Camp Fire in Butte County, California (165) where elevated benzene levels were also found in the water supply network affecting up to 40,000 people and over 2,400 private drinking water wells (165). Contamination and odour problems persisted for over 8 months after the fire, and heavy metals and PAH contamination were also reported in local creeks and rivers (165).

Contamination can persist for many years. Elevated nitrogen and dissolved organic carbon have been found in water catchment areas following wildfires for up to as 15 years (178). Slow forest and vegetation recovery after the 2002 Hayman fire is thought to have been responsible for persistent water quality concerns measured in 2015 (166). A study of 2 other California wildfires (the Rocky and Wragg fires in 2015) found that in addition to rapid water quality degradation due to elevated levels of turbidity, colour, and suspended solids, nitrate concentrations showed a marked increase in the second year, possibly due to delayed nitrification (167).

While wildfires can impact on large water catchment areas, these tend to be subjected to robust water treatment process. Areas without public or community water treatment such as private water supplies in the UK are likely to be more vulnerable to impacts on water quality or water security (179, 180).

While water is the main suppression method, it has its limitations, and during very intense fires may not substantially reduce the intensity and rate of spread of a fire. Firefighting foam is used in many countries and may minimise fire water run-off in the long term. However, such foams can include chemicals which have a range of uses such as surfactants, detergents, corrosion inhibitors, solvents, preservatives, stabilisers and anti-freeze agents. Such complex chemical formulations of fire-fighting foams can be problematic to the environment as fire-fighting run-off water is likely to contain a mixture of combustion products and residues of any chemicals present within the foam. Other complex chemical by-products can also be formed due to thermal degradation of the foam during fire-fighting activities. This can lead to the contamination of surface waters, groundwater, local aquifers and potentially drinking water supplies (181). However, no such contamination events have been documented in the UK.

6. Susceptible groups

The current evidence base demonstrates that some people and groups are more susceptible to the effects of wildfires than others. While the effects of ambient air pollution on children, the elderly and people with pre-existing health conditions have been well documented, it is clear that similar vulnerabilities exist among those exposed to wildfire smoke, especially among children (182 to 185). A cohort of children exposed to smoke from 2 large wildfires in Valencia, Spain was found to have increased respiratory symptoms, particularly in those with asthma (186).

Several studies have noted the detrimental impact that wildfires and other natural disasters can have on older people living with dementia, especially related to the impact evacuation can have on their mental health and ability to access healthcare (187, 188).

The social inequality of wildfires has also been noted in several countries, with socially vulnerable ethnic communities often being disproportionately affected, especially their ability to recover post-fire (189 to 191). Community wildfire plans can help identify which areas and communities may be poorly equipped to respond and recover from fires. This is already a potential issue in parts of UK, such as in Wales where the majority of wildfires occur in the South Wales Valleys, areas often with the lowest socio-economic status (6).

7. Mitigation measures

7.1 Sheltering and evacuation

In the UK, advice to shelter indoors is the main public health measure to reduce public exposure to smoke from fires, including wildfires. Buildings provide protection from outdoor pollutants because restricted air exchange and physicochemical attenuation (such as filtration, deposition and absorption as smoke passes through the building) mean that indoor exposures are lower, though they can increase over time as pollutants ingress. Many factors impact the effectiveness of sheltering, but in the context of prolonged fires, it is worth noting that outdoor concentrations are highly variable over time, changing with combustion conditions and wind behaviour. Buildings will protect people who are downwind from short-lived peaks in the concentration of outdoor pollutants. However, in the longer-term, it is not reasonable to expect or advise people to shelter indefinitely. A pragmatic approach is to use meteorological forecasts to determine times when populations will be downwind and sheltering should be employed, and times when they will not be downwind, and homes or buildings should ideally be ventilated to purge indoor pollutants. Some populations, for example, children and the elderly, are more susceptible to smoke exposure, and consequently require special consideration as they may be less able to tolerate prolonged exposures. During prolonged fires, some individuals may choose to leave their homes (self-evacuate); others may be unable or unwilling to do so.

Evacuations may be considered when there is an immediate risk to the public (such as a serious threat to life from the fire), or if evacuations can occur prior to a dangerous level of exposure taking place when an incident is likely to be relatively large or prolonged (for example, when sheltering poses greater risks than evacuation). In countries that experience large, severe and fast-spreading wildfires, evacuation is an integral part of protecting the public, and can be mandatory or advisory. Experience from North America and Australia demonstrates that human behaviour can be an important factor in the effectiveness of evacuation strategies, as some people may choose to stay (or return) home to protect their property (192, 193). However, poor decisions about when to evacuate can put people at risk of smoke exposure and can be life-threatening. In Australia, many fire-related fatalities are due to people leaving their homes and getting caught in the fire or smoke (49). Communities that are poorly prepared or do not understand the risks from wildfires are likely to make poor decisions when it comes to sheltering or evacuation.

Key factors when considering the practicalities and feasibility of evacuation are transport availability and suitability; the adequacy and availability of suitable evacuation routes and networks; time needed to evacuate; population size; mobility and special needs; physical considerations such as weather conditions; whether there are concurrent or related events that introduce additional hazards; and the time of day. Similarly, any decision to shelter and stay indoors to reduce smoke exposure needs to consider other concurrent hazards such as extreme heat or infectious diseases such as COVID-19, where the advice may be to improve indoor ventilation or stay in air-conditioned places.

7.2 Air quality guideline levels

Ambient air quality guidelines have been developed for many common ambient air pollutants including in the UK. However, their use as screening values during wildfires is limited as they encompass a relatively small number of pollutants and are not intended for use in scenarios involving abnormally high concentrations and short exposure periods, having often been developed for 24-hour averages or annual averages associated with the risks of exposure to ambient air pollution over a lifetime. Consequently, exposures during wildfires can be much higher than these standards. Fires are often associated with extremely high but short-lived peaks of PM, often reaching levels well above established ambient air quality standards. In common with air pollution indexes, such as the UK Daily Air Quality Index (194), advice regarding protective actions (such as sheltering indoors and limiting physical activity) is associated with a series of exposure categories based on time-weighted concentrations of PM.

7.3 Education and awareness

In countries that are commonly impacted by wildfires, such as North America and Australia, emergency responders, planners, policy makers and, above all, the public are aware of the risks from wildfires, usually as the result of direct experience. For example, houses and buildings built at the RUI without adequate fire-resistant measures are just another source of fuel (and pollution) during wildfires (195).

Public education and awareness of health risks and actions to take when properties and communities are threatened by a wildfire is key. Several international studies have emphasised the need to develop effective communication and education with the public (196 to 199) and there are already initiatives in the UK such as the Healthy Hillsides Project in Wales (129), StayWise and Firewise UK which have been working to raise awareness among key groups such as landowners and school children. Firewise UK is an initiative in Dorset which encourages communities to work together to make their homes more resilience to wildfire (200). It is supported by Dorset and Wiltshire Fire and Rescue Service, Dorset Police and Crime Commissioner and the Urban Heaths Partnership and provides practical advice to reduce the risk of wildfires around homes such as creating firebreaks, remove of dead vegetation and the need for a personal evacuation plan. StayWise is a free educational resource from UK emergency services to support teachers and community safety practitioners in delivering safety messages and includes learning materials and lesson plans on wildfires (201).

The Forestry Commission, funded by the Department for Environment, Food and Rural Affairs (Defra), also provides Lantra (land-based and environmental sector) accredited training for land managers, firefighters and researchers, covering wildfire mitigation in the RUI, community resilience, working with people, as well as incident response, with emphasis on safe systems for working to mitigate adverse impacts of smoke, on mental health, heat exhaustion and evacuation (202).

Public health professionals also need better education and awareness of wildfire risks. In the USA, the Centers for Disease Control (CDC) and Environmental Protection Agency (EPA) have published a resource guide for public health officials, which provides information on the health effects of smoke exposure, key public health actions such as sheltering, and guidance on populations at higher risk from smoke and heat exposure (203). The role of public health and the wider health care system in helping manage the risk from wildfires is significant, from raising public awareness, strengthening the health service response, working with responders to get timely messages out to affected communities and working with land managers and planners to reduce the risk of fire (204).

Many countries include smoke forecasts as part of their daily weather and air quality forecasts such as FireSmoke Canada (205). These forecasts can give individuals and communities the opportunities to prepare for wildfires by, for example, reducing outdoor activities and ensuring they have access to medication. Such early interventions can have a positive impact in reducing the effects of smoke exposure (206).

7.4 Habitat management

Habitat management has an important role in reducing wildfire risk. Options can include management of vegetation and fuels, the creation of fire breaks and fire belts, and improved landscape design (207). Management of vegetation to reduce fuel load is key and there are a number of ways to do this such as manual or mechanised cutting, thinning and felling of trees and managed burning. The use of fire-resilient species, changes in grazing practices and use of fire resilient features such as rivers and wetlands to fragment high-hazard areas can also greatly reduce the risk of wildfires. Fire breaks are natural or artificial gaps in vegetation, while fire belts are strips of fire-resistant species. Both create barriers that can prevent or reduce fire spread and fire breaks can also aid fire service response by creating access points to aid firefighting and the distribution of equipment. The location and design of fire breaks and fire belts requires knowledge of the wildfire risk of an area and will require input from both land managers and the fire and rescue services. Such measures can be built into current and future landscape design to improve wildfire resilience.

Where possible, the use of manual or mechanical cutting to remove fuel load from hillsides or to create fire breaks is recommended. In some circumstances, managed burning can also be used especially where large areas of fuel need to be removed. There are 2 types of managed burning: controlled (operational) burning is a fire within a secure perimeter where no breakouts are anticipated; while prescribed burning is a planned and supervised burn carried out under specified environmental conditions to remove fuel from a predetermined area of land and at the time, intensity and rate of spread required to meet land management objectives (208, 209). If done properly and with care, such burning has the potential to reduce wildfires, especially the likelihood of large, intensive fires. However, as with any fire, burning does not come without risks. Burning close to populated areas is likely to be poorly received by local people who may be concerned about the risk to their health and property (210). Burns can get out of control and can produce significant quantities of smoke, which under unfavourable weather conditions may impact air quality and human health (211 to 214). As a result, the adoption of prescribed or controlled burning should only be considered if manual/mechanised cutting or other habitat management options are not available and should take into account the prevailing weather conditions, proximity to local communities, road networks and major infrastructure. In the UK, the current legal burn season is heavily regulated, and typically runs between October to late March or early April in England and Wales (can be extended up to the end of April in Scotland). A wet winter and unfavourable weather conditions may limit the opportunity for safe prescribed burning, which may result in fuel load increases in wildfire prone areas. The likely lengthening of the wildfire season in the UK may also impact the window for prescribed burning.

Burning can also make some habitats less fire resilient such as peatlands where it can be detrimental as it moves the bog away from its original wet state and become less resilient to wildfires.

7.5 Land use planning

Flood risk is increasingly being integrated into land use planning and management. Plans and tools often include flood risk assessments, regulatory and building controls to limit development in areas of high flood risk, improving the capacity of open spaces and waterways to handle flood waters, for instance. As many wildfires in the UK occur at the RUI, there is a need to include wildfire risk in future spatial planning, linking to land management documents, such as Wildfire Management Plans, produced by the Forestry Commission (207). This will require coordination across building and urban design, and planning and land management. In several countries, including Australia and Chile, wildfire risk is already part of spatial planning (215, 216).

8. Current knowledge gaps and research priorities

While there is an emerging evidence base on the potential impacts from wildfires on public health, most studies are from other countries, notably the USA, Canada, Australia and, increasingly, mainland Europe. There is a clear lack of evidence on the health impact of wildfires in the UK. Improving this evidence base is vital to not only understand the current risks, but also to be able to understand and prepare for climate change impacts on UK wildfires in future.

We cannot simply extrapolate research and evidence from other countries. Smoke exposure in the UK may be very different to other countries. As discussed, most UK wildfires are relatively small and of shorter duration although some can occur in the RUI and close to populations. They may also involve different vegetation types compared to fires in other parts of the world, especially Australia or North America. Furthermore, our communities in the UK will not necessarily have the same underlying health and economic demographics as communities in other countries. As a result, it is important that we develop an evidence base on smoke toxicity and exposure that is relevant to the UK.

Climate change projections suggest the UK will see larger, more severe wildfires with more parts of the UK affected. As discussed earlier, a wildfire needs 3 essential elements – fuel, oxygen and an ignition source – and climate change is likely to increase the chances that each of these will be present (217). For example, further consideration is needed as to how climate change will affect type and flammability of vegetation in the UK and how more extreme weather such as lightning and strong winds may increase the chances of ignition and fire spread. Warmer, drier summers may increase outdoor recreational activity which may result in more people spending time in the countryside and increase the potential for fires to be started. The likely lengthening of the fire season may reduce opportunities for prescribed burning as a means of fuel management. Therefore, it is critical to understand how wildfires can impact communities in the UK.

8.1 Research priorities

More research is urgently needed to fill current knowledge gaps in UK wildfires and is essential in developing protection and intervention strategies and helping communities prepare for wildfires. Sufficient and stable funding is needed to address these research gaps which fall into 3 broad but interrelated areas and are described below.

8.1.1 UK Wildfire smoke composition and emissions

There needs to be a better understanding of the composition of smoke from UK wildfires. While there is a growing evidence base on the composition of wildfire smoke, especially around key pollutants such as $PM_{2.5}$, the exact composition will differ due to the material being burnt, the combustion conditions and underlying meteorological conditions. Research is needed to characterise emissions from a range of different UK vegetation types and combustion conditions (flaming and smouldering phases) using bench, laboratory and large-scale studies. Data on how fire emissions affect the soil and water environment would also be beneficial.

8.1.2 Exposure assessment

Understanding how people are exposed to smoke from wildfires in the UK is key to any health study and is needed to aid the public health response during a fire. Methods to assess exposure can include air monitoring during wildfires, the use of satellite imagery and dispersion modelling. Evidence from the Saddleworth Moor fires shows how air quality can be affected both locally by $PM_{2.5}$ and regionally through the formation of O_3 downwind (8). This research is a rare example from the UK. Consideration is needed to explore how to improve air monitoring during large wildfires and what pollutants will need to be monitored as this can also inform public messaging and warning before and during wildfire events. The AURN is the main air monitoring network in the UK but is based on fixed urban and rural monitoring stations providing data on ambient air quality around main road networks and industry. Most AURN sites are not located in wildfire prone areas and unless downwind of a fire, they will not collect data related to wildfires. Furthermore, they typically measure common air pollutants related to traffic and urban air and, while some do monitor for PM, they will not measure many of the other pollutants associated with wildfire smoke.

There is already capacity in the UK to deploy mobile air monitoring units to industrial accidents and waste fires, for example the Air Quality Cell arrangement managed by the Environment Agency in England, while low cost portable sensors are being increasingly being used to monitor ambient air pollution. Both offer the ability to be deployed to monitor air quality in communities affected by wildfires.

8.1.3 Health studies

Population health studies are needed to better understand the short and long-term impacts of smoke from UK located wildfires. Evidence from other countries shows that wildfires can cause respiratory and cardiovascular effects in people, which can manifest in increases in hospital admissions, use of medication or visits to GPs. There is also increasing evidence that wildfire smoke exposure can potentially impact all-cause mortality. It is currently unclear whether communities exposed to wildfires in the UK experience such negative impacts now and in the future. Research is required to model both mortality and morbidity from wildfire smoke exposure under different climate change scenarios. Further consideration is needed on other health outcomes, such as the impact of wildfires on mental health and the influence of co-exposures with other threats to health, for instance, heat during the summer. More research is also needed to better understand the impacts of wildfires in drinking water catchment areas.

8.1.4 Other research needs

Wildfires are often started accidentally or deliberately, and climate change is likely to have an impact upon the extent and severity of the consequences to starting a fire. More research is needed to evaluate approaches to increasing public awareness and the responsible behaviour of users accessing wildfire prone areas, and to help manage the use of green spaces while reducing wildfire events.

Other knowledge gaps include the impact of UK wildfires on greenhouse gas emissions. Wildfires will emit gases such as CO_2, CO and CH_4, and deep burning fires in peatland may also release stored carbon (218). While UK wildfires may be small compared with those elsewhere, more research is needed to understand the how emission may contribute to climate change.

8.2 Public health implications

It is likely that in the future an increased number of people in the UK will be exposed to wildfires. Public health guidance and climate adaptation strategies need to help communities prepare for, respond and recover from wildfires. This could include supporting communities to be more firewise, raising awareness of the risks from wildfires, especially smoke and air pollution and better public and social media messaging around wildfires. As wildfires can occur concurrently with other climate change hazards such as heat, drought and so on, it is vital that that wildfire risk prevention is considered as part of an all-hazards approach. This will require coordination and collaboration across a range of government and non-government stakeholders. Initiatives such as the UK Home Office-led Wildfire Framework for England and the Wildfire Charter for Wales can help ensure the engagement of all relevant stakeholders. Education and community engagement is vital to help with behavioural and cultural changes and public health professionals can play an important role in working with other partners and stakeholders in raising awareness of hazards associated with wildfires.

9. Conclusion

The impact of climate change on increased episodes and intensity of wildfires will likely have a significant impact on public health. The increased morbidity and mortality associated with wildfires is evident, not only the effects of reduced air quality and its potential effects on the health of the public, but also on the environment. However, the short and long-term effects on health due to increased wildfires in the UK is poorly understood, despite studies in other countries and more work is needed to address this.

Wildfires are a complex problem that require multi-agency response. Early warning is a key aspect of health protection, along with engagement with local communities to ensure they are involved in planning and preparedness for response during a wildfire event. There needs to be a greater understanding of the impact of UK wildfires and needs to consider different vegetation types, their products of combustion, toxicity and pathways to public exposure and the subsequent health effects. In addition, the environmental impacts on water and soil quality may also have a long-term effect on local communities, and there needs to be further studies on how to work with communities and responders to minimise the consequences of wildfires.

Acronyms and abbreviations

Abbreviation	Meaning
AURN	Automatic Urban and Rural Network
CH_4	methane
CI	confidence interval
CO	carbon monoxide
CO_2	carbon dioxide
COPD	chronic obstructive pulmonary disease
DHA	daily hazard assessment
FSI	fire severity index
NFCC	National Fire Chiefs Council
NO_X	nitrogen oxides
O_3	ozone
OR	odds ratio
PAH	polycyclic aromatic hydrocarbons
PM	particulate matter
PM_{10}	particles smaller than (<) 10µm diameter, referred to as coarse particles
$PM_{2.5}$	particles smaller than (<) 2.5µm diameter, referred to as fine particles
PTSD	post-traumatic stress disorder
RR	relative risk
RUI	rural-urban interface
SO_2	sulphur dioxide
VOCs	volatile organic chemicals
WUI	wildland-urban interface

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UKHSA is an executive agency, sponsored by the Department of Health and Social Care.

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Published: December 2023
Publishing reference: GOV-14571

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