

UK Wildfires and their Climate Challenges

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Introduction

Climate change is recognised as a defining issue for the future of the planet and humanity, requiring co-ordinated actions both internationally and nationally. The UK is distinctive amongst nations in having formalised a statutory framework for climate change action (Climate Change Act, 2008). In addition to providing the basis for greenhouse gas reductions (climate change mitigation), this framework places an obligation on the UK government to conduct a Climate Change Risk Assessment (CCRA) every 5 years in order to inform climate change adaptation planning through risk management. The cycle has now reached the 3rd CCRA with previous CCRA evidence reports having identified wildfire risk as an important cross-cutting issue but also identifying gaps in knowledge which may be impeding action. In terms of urgency of action, the CCRA2 evidence report therefore categorised wildfire risk under ‘Sustain Current Actions’, but recognised knowledge limitations in making this assessment. The UK Government Adaptation Programme therefore followed this recommendation.

The CCRA takes place alongside other government risk management processes. Emergency and contingency planning has usually had a focus on identifying near-term threats to UK security as formalised through the national risk register and its link to local planning. In addition, the Climate Change Act (2008) included provisions for an Adaptation Reporting Powers (ARP) component through which key agencies, businesses and other organisations would report on their progress on adaptation risk management. This was originally required as mandatory for a series of essential services and businesses but after CCRA the procedure was made a voluntary opt-in process. The evolving dimensions of these governance arrangements and also the co-ordination between national policy and actions at local level or by other stakeholders therefore remain a key issue for adaptation risk management.

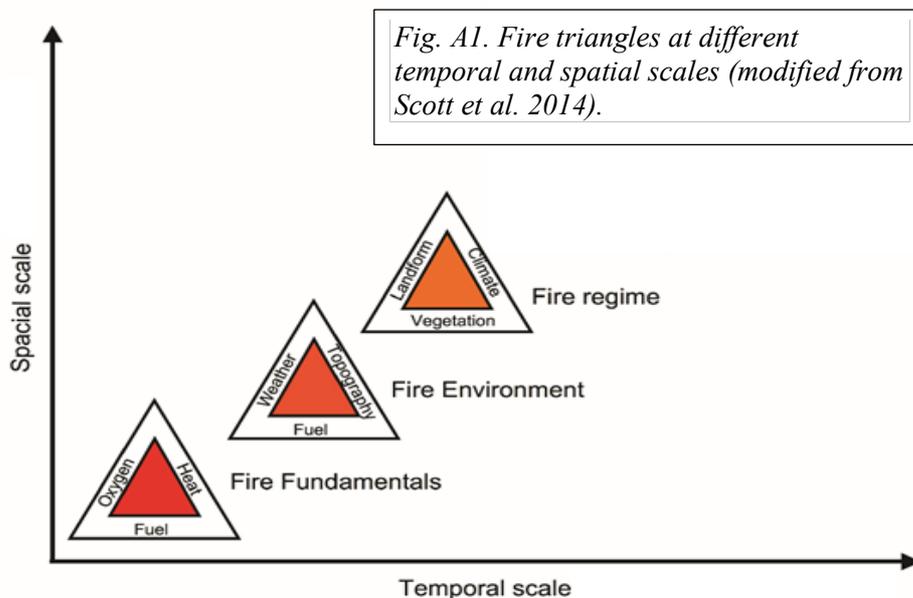
With the 3rd UK CCRA now underway it was identified that a more comprehensive assessment of wildfire risk was required, engaging a wide range of scientific expertise to assess current knowledge and the role of current procedures in managing risk. This recognised that considerable new knowledge was available, not just in the UK but with the prospect of learning from broader international research activities and lessons learnt from countries that have, so far, experienced more severe wildfire impacts.

The aim of this CCRA report is to assess the magnitude of present and future wildfire risk in the context of climate change (including both direct and indirect climate relationships), together with the response to that risk in terms of adaptive risk management (i.e., recognising that risk is dynamic and that this can affect residual risk). If necessary and if supported by evidence, additional actions to reduce the residual risk may be investigated and potentially recommended. By defining wildfire risk as ‘cross-cutting’, the CCRA has recognised that although traditionally associated with sectors of the natural environment, the risk also has implications for people, buildings, infrastructure, and businesses, and therefore crosses the rural-urban interface.

In the following sections, we firstly identify how ‘wildfire’ is defined in the UK and outline its relationship to the natural environment and climate. Then we assess evidence for changes in current wildfire risk in the UK and how this may change in the future (directly or indirectly), including how climate change may interact with other socioeconomic drivers. This information is then used to contextualise current wildfire policy and actions in the UK, providing a basis to consider where further actions may be beneficial in reducing residual risk.

A) What are Wildfires: the UK Context

In the global context, a wildfire is any non-structure fire, other than prescribed fire (i.e., fires lit to manage fuel load for dangerous fire prevention or for ecological management), that occurs in a wildland. Wildfire has been an important element on the Earth over the past 400 million years. For a fire to start and spread, it needs three key elements which are usually referred to as the ‘fire triangle’: oxygen, ignition source and fuel (Fig. A1). At the landscape scale, the three elements of the fire triangle are weather, fuel and topography (Fig. A1). The interactions of these factors are key to understanding fire behaviour and how intrinsic and extrinsic factors condition it. For example, the effect of climate change enhancing fire activity, already observed in many regions around the world, is mostly via an increase in fuel availability (i.e., dry vegetation available to burn) and lengthening of the fire season (i.e., days when meteorological conditions are conducive to fire) (Jones et al. 2020). Indeed, rising atmospheric carbon dioxide levels have been linked to increased fire activity at many times over the multimillion-year history of our planet (e.g., Baker et al., 2020).



In the UK, the term wildfire is officially defined as ‘any uncontrolled vegetation fire which requires a decision, or action, regarding suppression’ (Scottish Government, 2013). This definition differs from the international term given above as a fire ‘that occurs in a wildland’ because the UK no longer has many true wildland areas (Gazzard et al. 2016). It therefore includes not only vegetation fires occurring in woodland, grassland and shrubland areas but also smouldering fires, that are common in peat, and fires in built-up areas with vegetation and gardens.

Wildfires in the UK are considered a semi-natural hazard due to their close link with human activities that stem from land management practices through to the social causes of accidental and arson ignitions (Gazzard et al. 2016). At the same time, it is also essential to recognize that wildfire has many positive impacts such as the maintenance of key habitats, the rejuvenation of vegetation and the control of pests and diseases. In fact, the use of fire by humans has been common practice in the UK for centuries, particularly as a landscape tool to create suitable land

for grazing and agriculture. This has resulted in the UK being a mosaic of fire-adapted landscapes, that have high natural and cultural value, such as heathlands and upland moorlands. The decline of traditional land uses and practises, which include fire, and lack of alternative holistic fuel management practices has been suggested to be threatening the conservation of these ecosystems and increasing the risk of severe wildfires (Allen et al. 2016). Although other proposals for management strategies exist (Natural England, Glaves et al., 2020)

In the UK, fire activity is mostly limited by fuel moisture conditioning and fuel availability, i.e. amount of dry vegetation or soil (i.e. peat) susceptible to burn, hence it does not have to be warm for fires to occur in the UK, in fact fires often occur in dead and dry winter fuels. However, there are usually two fire seasons, the main one in spring and a secondary one in mid-late summer. The majority of wildfires occur in grasslands and broadleaved woodlands although, in terms of the size of area, heathlands, moorlands and grasslands present the largest burnt areas. The intensity of most UK fires is usually low to moderate, with fire mostly affecting surface fuels (grass and shrubs; Fig. A2), although crown fire behaviour has been known to occur in conifer forests (e.g., Swinley Forest, 2011) (Fig. A3) as well as smouldering fires in peat soils (see Case Study in section B of Saddleworth Moor). A great proportion of fires affect vegetated areas in close proximity to built-up areas, which is an important factor to consider in regards both the risk to human health and assets) (Fig. A4). This makes UK wildfires as particularly challenging in regard to both their risk and threat.



Fig. A2. Examples of prescribed fire (left) and wildfire (right) in Welsh grasslands.



Fig. A3. Examples of crown fires in the UK (Swinley fire image credit Rob Gazzard).



Fig. A4. Many wildfires in the UK occur in the proximity of built up areas (South Wales, April 2020; credit Craig Hope).

B) The Nature and Impacts of UK Wildfire - Case Studies

Previous analysis of Fire and Rescue Service (FRS) data has shown that annual response costs for fires in 2009/10 and 2010/11 amounted to £55 million alone and can be very much larger in years with prolonged hot dry periods (e.g. 2003, 2006, and 2011, 2018, 2019). Other financial costs include loss of grass and arable timber revenue and replanting costs and landscape-scale restoration costs (e.g. in Peak District and South Pennines, recurring peat fires required £16 million for restoration).

Severe fires which burn into dry peat result in a net loss of carbon via greenhouse gas emissions (e.g., CO₂, CH₄), loss of biodiversity, and impacts on scenic sites and water quality through erosion and eroded peat entering upland reservoirs; these peat-fed catchments reservoirs are important in terms of potable water extraction (Xu et al., 2018). Potential peat loss through smouldering fires is particularly important in the UK as it holds a disproportionately large area of peatlands for its size. Smoke can lead to air quality issues, road closures, evacuations (e.g. in the Swinley fire three schools and many houses). Vegetation fires also incur significant operational costs for FRS; even small, frequent, and simultaneous fires put pressure on increasingly squeezed resources, taking them away from property fires and traffic accidents. We provide in the following some example case studies of significant UK wildfires that capture some aspects of the impacts and challenges faced.

Impacts on Major Infrastructure and Assets – Swinley Forest and Crowthorne Wood

Late April and Early May 2011 saw an unprecedented number of wildfires in grass and heathlands, owing to high temperatures and little rain coupled to strong winds. These led to the largest and most resource intensive wildfire in Berkshire's history. The fire started in Swinley Forest and spread to Crowthorne Wood, the former managed by the Crown Estate and the latter by the Forestry Commission. The crown fire affected 300 hectares and required 300 firefighters from seven brigades to contain the fire.



Fig. B1 Swinley forest fire, May 2011 image credit Rob Gazzard.

The fire spread through 7 hectares of forest plantation in 20 mins and flames jumped the 10m wide fire breaks that would protect fire spread under “normal” UK fire conditions (Fig. B1). The fire burned for 7 days. This fire presented a significant challenge owing to its high intensity, despite the area affected being much smaller than many moorland fires, the assets at risk in the forest-urban interface made the incident politically significant. The fire jumped and

ran along a large section of the A3095 which had to be shut, and its proximity to major infrastructure led to significant challenges.

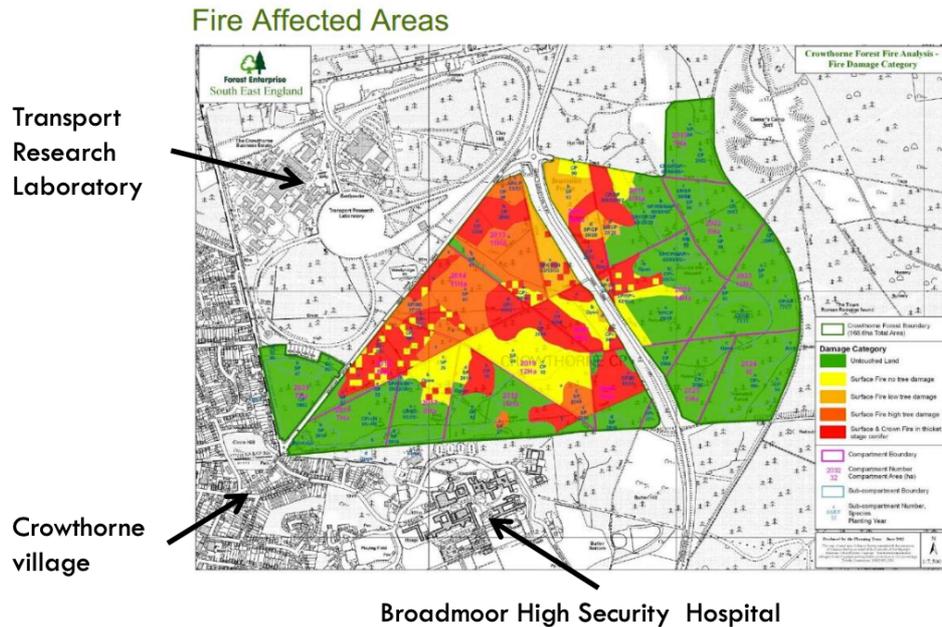


Fig. B2 Map of key infrastructure and damage class for Swinley/Crowthorne Forest Fire. Red surface and crown fire, dark orange surface fire high tree damage, orange surface fire low tree damage, yellow surface fire no tree damage, green unaffected land.

The fire threatened national infrastructure, including Broadmoor High Security Hospital, the Transport Research Laboratory, a trunk fuel pipeline, Crowthorne Village and Sandhurst Royal Military Academy (see Fig. B2) Seven houses were evacuated; three schools were closed; local businesses incurred losses up to £70,000. The fire-fighting costs have been estimated at £543,000 (Aylen et al. 2011), transport costs owing closure of a major A-road for five days - £229,300. Whilst, replanting of the woodland lost, is likely to have been over £150,000 (Oxborough and Gazzard, 2011; Aylen et al., 2011). The total social cost of the incident has been estimated at ~£1,129,700, which did not included estimates as to loss in regard to ecosystem services.



Fig. B3 Smoke from the fire in Crowthorne Forest

Impacts on Communities and Homes – Wandstead Flats and Iping Common

UK wildfires do not need to be intense crown fires to cause impact on homes and communities as demonstrated by the Wandstead Flats wildfire, London, on the 15th and 16th July 2018.



Fig. B4 Wandstead Flats fire - credit National Police Air Service

The Wandstead Flats wildfire has been named as London’s ‘largest ever grass fire’ (Dany Cotton, London Fire Commissioner), where at the height of the fire, more than 100 hectares were alight and smoke drifted across busy roads, causing local road closures. The fire required more than 225 firefighters and 40 fire engines and required 100 to remain for two days to dampen down the ground. The fire was a threat to a large residential area (see Fig. B4), over 100 people were evacuated, and one firefighter was injured. The fire burnt 100% of an Epping Forest SSSI unit of recovering acid grassland. This destroyed an important habitat that was home to many bird species, including the Skylark, Meadow Pipit and Whitethroat.

UK wildfires can occur out of season such as that which occurred at Iping Common (Fig. B5), West Sussex on the 28th February. Despite a Met Office warning of snow, extreme temperatures (-2.5°C) and snow and ice across the country, the strong winds associated with this icy blast dried out an area of lowland heath that was subject to ignition by a bonfire. The fire was driven as a long fireline by 13mph winds that gusted to 27mph, caused part closure of the A272 for ~3 hours but luckily was contained by 8 pumps, 6 land rovers, 1 Uni Mog, 1 command unit and 1 water carrier before it reached residential properties to the west. The fire burned 30 hectares of SSSI heathland.



Fig. B5 Iping Common fire

Impacts to Industry and Agriculture – Little Marlow



Fig B6 wildfire in a corn field, Pump Lane, Little Marlow

UK wildfires are common in agricultural lands and not only pose a threat to loss of crops and agricultural income but also to properties and other assets in the area. In early July 2018, during heat wave conditions ($>25^{\circ}\text{C}$) an incident occurred where fields being cut by a combine harvester were ignited and a fire spread rapidly through both cut and standing crops (Fig. B6). 100 firefighters and 40 pumps tackled a wildfire in a field that spread to nearby industrial units. The smoke from the fire closed the A494 at peak rush hour (which feeds into the M4 and M40). 12 residential properties were evacuated and after 1 hour the fire reached commercial property at Pump Farm. The fire led to the loss of a residential property and 2 industrial units (Fig. B7).



Fig. B7 Pump Farm and Industrial Units, Little Marlow. Credit Buckinghamshire Fire and Rescue Services

Whilst the fire itself was small (just 30 hectares) it had considerable impact via its destruction and damage to a residential home, commercial properties, 4 commercial vans and threatened an electric substation as well as causing disruption to travel (closure of the A404 for 2 hours) and local businesses.

Impacts on Ecosystem Services – Saddleworth Moor

Wildfires not only consume live and dead biomass with direct ecological consequences, and emit atmospheric pollutants as discussed below, they can also affect other ecosystem processes, such as soil, hydrological and biochemical cycles (Harper et al. 2018). These impacts can alter the ability of an area to provide Ecosystem Services, which are “conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life” (MA 2005). Important ecosystem services include water and food provision, climate regulation (e.g., via carbon storage) and recreation (MA 2005). For example, in regions adapted to fire, burning can promote opportunities for grazing animals, which in turn increase human food provision (Pausas and Keeley 2019). Reduced plant water use and enhanced surface water runoff after fire can also increase the quantity of water reaching water supply reservoirs (Shakesby and Doerr 2016), an advantage in regions with water scarcity. However, this water is often of lower quality, containing sediment and potential pollutants from eroded burned soil and wildfire ash.

The Saddleworth Moor wildfire (1.96°W, 53.54°N) (more correctly known as the Stalybridge wildfire), which occurred during an exceptionally dry period in 2018, was amongst England’s largest wildfires in recorded history (Graham et al. 2021). The fire ignited on 24 June, was declared a major incident on 26th June, and burned for over 3 weeks, with the military assisting in its suppression. It affected over 18 km² of upland terrain (Fig. B8 and B9) that supplies the greater Manchester area with drinking water. The fires burned on moorland dominated by heather with an underlying layer of peaty (organic-rich) soils, that have elevated heavy metal levels due to a long legacy of airborne deposition from heavy industry in this region (Kettridge et al. 2019). Both vegetation as well as the relatively dry organic soil acted as fuel, making the suppression of this fire very challenging and impacting the area’s ecosystem services. Climate regulation was affected by the loss of vegetation and organic soil biomass. While the vegetation biomass is recovering relatively well in this humid temperate climate, the organic matter (peat) that had accumulated over many centuries that was consumed in the fire presents a longer-term loss of carbon to the atmosphere (Fig. B8a and b). Average soil burn depth in the most severely affected areas was estimated at 6 cm. Overall, the fire emitted an estimated 36,720 t of C, with the majority being long-term losses from peaty soils. This is equivalent to the annual emissions of ~86,000 UK passenger cars (Clay, Belcher, Doerr, unpublished data).



Fig. B8: a) The Saddleworth Moor wildfire area on 10 July 2018. b) Smouldering combustion burning deep into peaty soil. c) Thick ash deposits left behind at a severely burned area. (Photos S. Doerr)

Water provision was at risk as the consumption of peaty soils left behind substantial ash deposits (Fig. B8c), which are typically enriched in nutrients and metals (Smith et al., 2011). This was a particular concern where the fire burned steep slopes directly adjacent to the Higher Swineshaw water supply reservoir (Fig. B9a). Ash quantity, composition, contamination risk and mitigation options were examined in collaboration with the catchment’s manager, United

Utilities. Ash cover was ~36 t/ha with concentrations of water-soluble heavy metals being 1-2 orders of magnitude above those found in wildfire ash from wildland areas in other countries (Swansea University, unpublished data). Owing to (i) the lack of rainstorms of a magnitude that cause substantial erosion in the months before large-scale vegetation recovery (Fig. B9b) and (ii) mitigation treatments implemented by United Utilities (Fig. B9c), the water supply has remained unaffected to date.



Fig. B9: a) Severely burned terrain above the Higher Swineshaw reservoir. b) View of the same area in Feb. 2020. c) Installation of biodegradable netting on the reservoir edge to prevent ash and soil erosion. In the foreground is a black erosion fence to trap sediment for monitoring purposes. (Photos S. Doerr)

Impacts on Air Pollution and Health – Case Study Saddleworth Moor.

Wildfires can be a major source of atmospheric pollution. Wildfire emissions include both gases and particulate matter (PM). Criteria air pollutants emitted directly from wildfires include carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter in the inhalable and breathable fractions (PM_{2.5}, PM₁₀). Wildfires also emit volatile organic compounds (VOCs) that lead to the secondary production of criteria air pollutants, such as ozone (O₃). The most important immediate health risk posed by air pollution from wildfire smoke is the onset of acute lower respiratory disease (ALRI) as a result of high concentrations of PM_{2.5}. The impacts of wildfire emissions may also exacerbate symptoms of chronic conditions, such as chronic obstructive pulmonary disease (COPD), cerebrovascular disease (CEV), ischaemic heart disease (IHD), and lung cancer; increasing the overall mortality risk for those who are exposed. The Saddleworth Moor wildfire (Fig. B10) was a large wildfire that broke out on 24 June 2018 and continued to burn for three weeks. The fire produced a thick smoke plume that was blown west over Greater Manchester, extending as far as the west coast of England and the north coast of Wales. Concentrations of PM_{2.5} were significantly elevated in Greater Manchester, as well as urban centres up to 80 km from the fire (Liverpool and Wigan, see Figure B11). A recent study by Graham et al. (2021) found that 4.5 million people were exposed to concentrations of PM_{2.5} that were above the World Health Organisation's 24-hour guideline limit of 25 µg m⁻³ for at least one day during the wildfire event. Graham et al. (2021) investigate the excess mortality in the affected areas during the Saddleworth wildfire air pollution event and ascribe that up to 60% of excess mortality downwind of the fire was due to the wildfire's air pollution – being responsible for around 4 deaths. They also calculate that the economic impact of the mortality due to PM_{2.5} from the fire amounted to £21.1m.

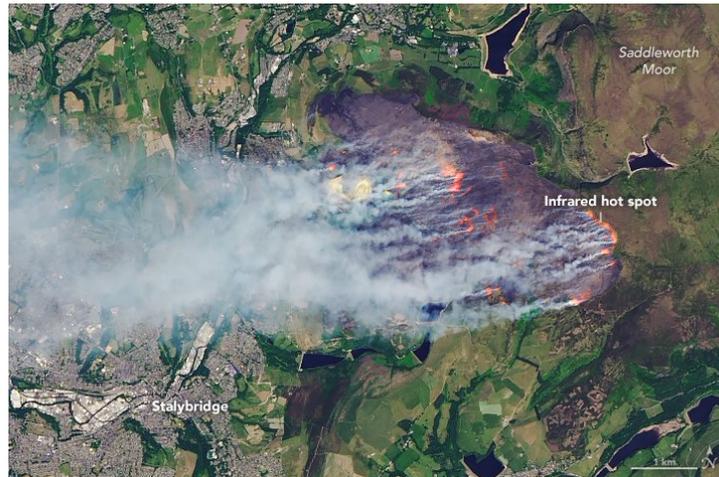


Figure B10. (Landsat) Satellite image of Saddleworth fire showing burnt area, active burning (glowing orange), and the smoke plume dispersing to the west over the suburbs of Greater Manchester.

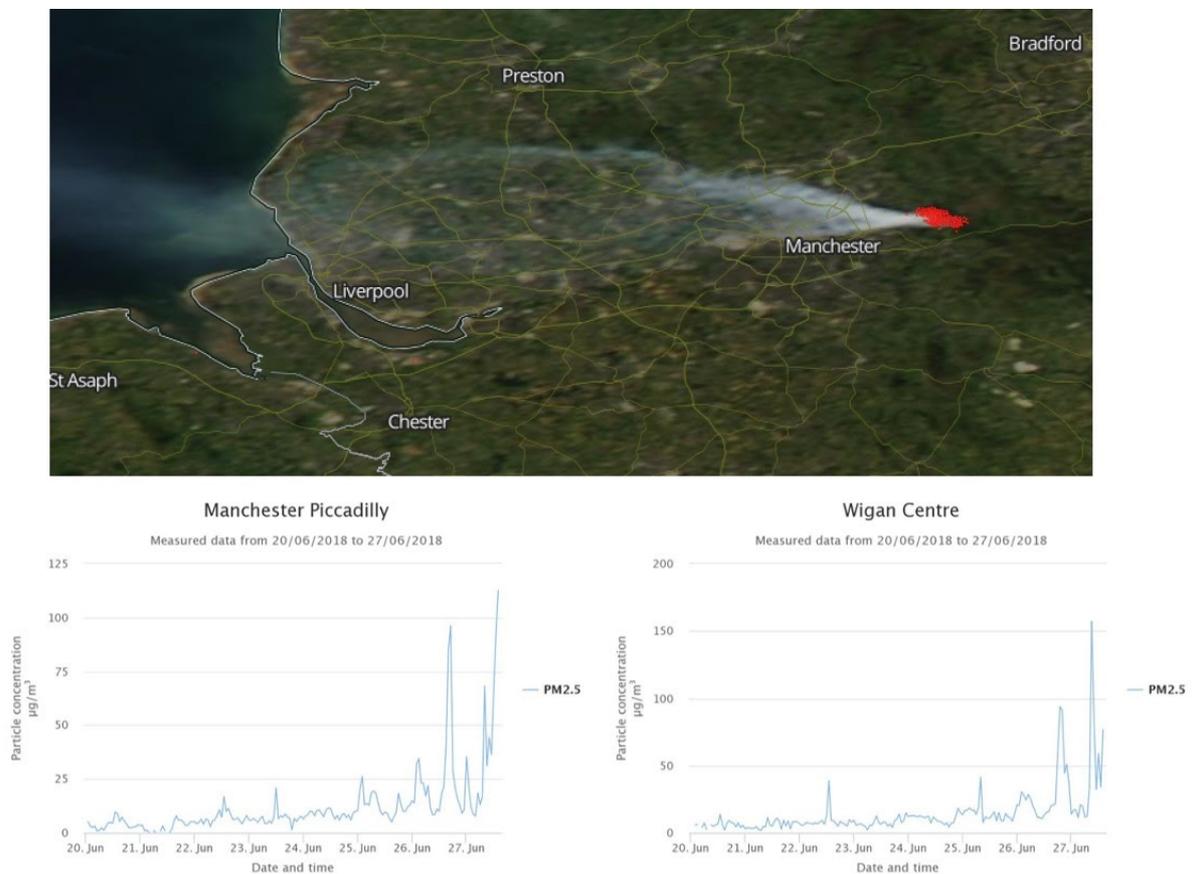


Figure B11. (top panel) Wider satellite view of the Saddleworth wildfire (MODIS), showing active fire hotspots (red), and smoke plume over Greater Manchester, northern Liverpool, and over the Mersey estuary. (bottom panel) Time series of particulate matter ($PM_{2.5}$) concentrations at Manchester Piccadilly and Wigan Centre showing background levels and significant spikes during the Saddleworth wildfire.

Impacts on Infrastructure and Fauna and Usage of Tactical Burns – Case study Wareham Forest Fire 18th May 2020

The spring of 2020 saw some exceptional weather in Dorset. It was the sunniest April in a series from 1929 with 255 hours of sunlight. It was also the warmest April since 2011, and the 4th warmest in a series from 1884. Due to a wet end to the month, it was only the driest April since 2017, but until the last few days it had been very dry. May was the second record-breaking sunny month in a row, the sunniest May in a series from 1929 with 335 hours of sunlight, beating the previous record set in 1989 by a large margin (May 1989 had 295.7 hours). It was the warmest May only since 2018, with the frequent clear skies leading to relatively cold nights. It was the driest May since 1896, and the second driest May in a series from 1862. Wareham Forest is a large Forestry England site of mixed coniferous plantation, heath and bog. It sits on mostly sandy soils of the Poole Basin.

At 12:23 on the 18th May 2020, Dorset and Wiltshire Fire and Rescue Service (DWFRS) responded to a report of a wildfire at Wareham Forest. The Forestry England (FE) Wildlife Ranger was on scene first and witnessed a rapidly developing fire moving quickly through the young pine plantation. It was being driven by a strong, 12 to 15mph, Westerly wind. Despite the best efforts of fire crews, the fire quickly reached, and jumped, Sugar Hill Road. 25 major pumping appliances plus several specialist off road firefighting vehicles and water carriers were ordered onto the incident. In the first day, the fire covered 188 hectares (Fig. B12a). It was declared a Major Incident and additional resources were requested for the second day including National Wildfire Tactical Advisors, the Forestry Commission Wildfire Advisor and High-Volume Pumps HVP.

Over the next two weeks a total of four HVPs were used to create a temporary over ground water main of 11km in length supplying an estimated 4 million litres of water to the fire ground. All 50 DWFRS Fire Stations attended the incident with 70 of the 74 pumping appliances being used including all eight Heavy Off Road Pumps plus all 14 Light Off Road Pumps and a Unimog. In addition, 22 pumps attended from other Fire and Rescue Services. This had a significant impact on the resilience of the FRS for an extended period. By the close of the incident, it had lasted for more than 2 weeks and had covered a total area of 226 hectares.



Fig B12 a) View of Wareham Forest Fire from NPAS helicopter b) Backing fire in pine plantation. Photos taken and provided by Andy Elliott.

The land Management sector also played a significant role at this incident. FE and their partners from the Urban Heaths Partnership (UHP) provided several off-road pumping appliances including fogging units and water bowsers. Two tractor mounted mulchers were used to

strengthen fuel breaks and to create new fire defensible lines through some tough terrain and earth moving equipment was in constant use repairing the forest tracks to keep the whole operation mobile.

There were a number of ‘firsts’ for DWFRS. This was the first incident that a helicopter was used to ‘bomb’ the fire, the first time a bulldozer was used to cut fire defensible lines and the first time that chainsaw crews were brought into play to provide access to some particularly difficult hot-spots. DWFRS also brought in the assistance of a Tactical Burn Team from South Wales FRS to burn off some areas of fuel to reduce the risk of re-ignitions jumping tracks and fuel breaks (Fig. B12b).

During the incident, a high voltage cable system had to be shut down. This was a part of the National Grid that crosses the site carrying power to a large part of the South West. This did not cause disruption to service, but significantly reduced the resilience of the network delivery to the South West. The High-Pressure oil pipeline from the Wytch Farm oil installation runs through Wareham Forest but was not affected by this incident.

Wareham Forest is home to many of the UKs rarest reptile species. Several of these lost their lives during the fire, but many more will be directly impacted by the loss of their habitat; their home. The environmental impacts spread beyond just reptiles and amphibians. Many species of birds were nesting at the time including the rare Dartford Warbler, a ground or near ground nesting species (Fig. B13). It will take many years for these habitats to recover fully, probably between 20 to 30 years to reach the pre-fire status.



*Fig. B13 a) Dartford Warbler Nest, b) Common Toad Andy c) Rescued Sand Lizard
Photos taken and provided by Andy Elliott.*

In the heart of the fire was Woolsbarrow Camp, a late bronze age, early iron age hillfort. This is a Scheduled Ancient Monument and it was burnt over completely during the fire. The forestry crop was mostly destroyed by the fire. Some of this will be harvestable, but much of it was still too young to be of use. The future of these plantation areas is undecided, but the impact on the landscape will be long lasting.

C) Drivers and Trends in UK Wildfires

As highlighted by the Case Studies above, the UK routinely experiences wildfires, typically with peak activity during the spring and mid/late summer, due to a combination of factors including fuel conditions conducive to carry fire and human activities. Climate directly affects fire activity through its influence on 'fire weather', which are the preceding and current conditions that allow vegetation to be ignited and carry a fire. The flammability of vegetation is principally controlled by its moisture content as water absorbs heat, dilutes the flammable volatiles in vegetation and excludes oxygen from the combustion zone (Finney et al., 2013).

Assuming that there is sufficient fuel to carry a fire, the ignition and spread of wildfires, are fundamentally controlled by the balance of precipitation and temperature over hourly, daily and seasonal timescales. These two factors are combined in the measure known as relative humidity (RH), which is the ratio (%) of the partial pressure of water vapour to the equilibrium pressure of water at a given temperature. The RH% describes the amount of water in the air relative to the amount of moisture required to saturate the air at a given temperature and pressure. This balance is important in regard to wildfire because it influences live fuel moisture and determines dead fuel moisture where the moisture of fuel determines whether or not a fuel is capable of being ignited and carrying a fire. Fuel moisture therefore, influences both flammability and fire behaviour (Arganaraz et al., 2018).

The fuels of an ecosystem have a range of differently sized components and some may be dead, and some may be live. Dead fuels will include dead leaves, twigs and branches; these may be retained on plants or shed to form a dead fuel layer on the ground. Dead fuels respond differently to changes in precipitation and relative humidity than live fuels and are the primary fuels within which a fire will be initiated. This is because dead fuel moisture is solely controlled by the environmental conditions, because the plant parts can no longer actively draw in water or respire water vapour and therefore the interaction of conditions that influence relative humidity ultimately determine dead fuel moisture content. For this reason, dead fuels are divided into four "time lag" classes (e.g. Schlobohm and Brain, 2002). These are 1-hour, 10-hour, 100-hour and 1000-hour fuels. These fuel categories relate to particles of different diameter; $\frac{1}{4}$", $\frac{3}{4}</math>"-1", 1"-3", 3" to 6" diameters respectively and are described as timelag fuel classes because their fuel moisture is described by the time necessary for each fuel size class to reach 63% equilibrium between its original moisture content and that of the current conditions (Schlobohm and Brain, 2002). Hence, 1-hr fuels take 1hr to equilibrate whilst, the largest fuel class e.g. fallen trunks for example may take up to 1000hrs. Hence the resulting fuel moisture of larger fuel classes will be the integral over a long time of the daily changes in RH%. Note that equilibration to RH% can be either the drying or wetting of fuel. Because of this relationship, fine, 1-hour dead fuels are the most important fuel type in regard to ignition and initial spread of wildfires. If these fuels are too moist, either via there having been extensive rainfall or low temperatures, then ignition will not be achieved, and a fire cannot spread.$

Low rainfall and humidity as well as high temperature and wind dry out the fuel, and therefore increase its flammability. A higher air temperature, for example, leads to more rapid and intense drying of fuel. The above factors combined also lead to more intense fire behaviour. Strong winds, for example, lead to more rapid transport of oxygen to the flaming zone, which in turn leads to more rapid combustion, greater flame length and faster spread rates. Such relationships can be described as Fire Weather and these factors can be quantified into daily Fire Weather Indices (FWI) and incorporated into regionally defined Fire Danger Rating Systems (FDRS). These are used to identify fire risks at various extremes (e.g. 'high', 'severe'

and ‘extreme’) used to inform management decisions. An example estimation of a fire weather index based estimate by the UK Met Office is shown below (Fig C1) for 18th May 2020, which is the day the large Wareham forest wildfire started and shows a very high (orange colour) fire weather index (‘fire severity index’) for the Wareham area.

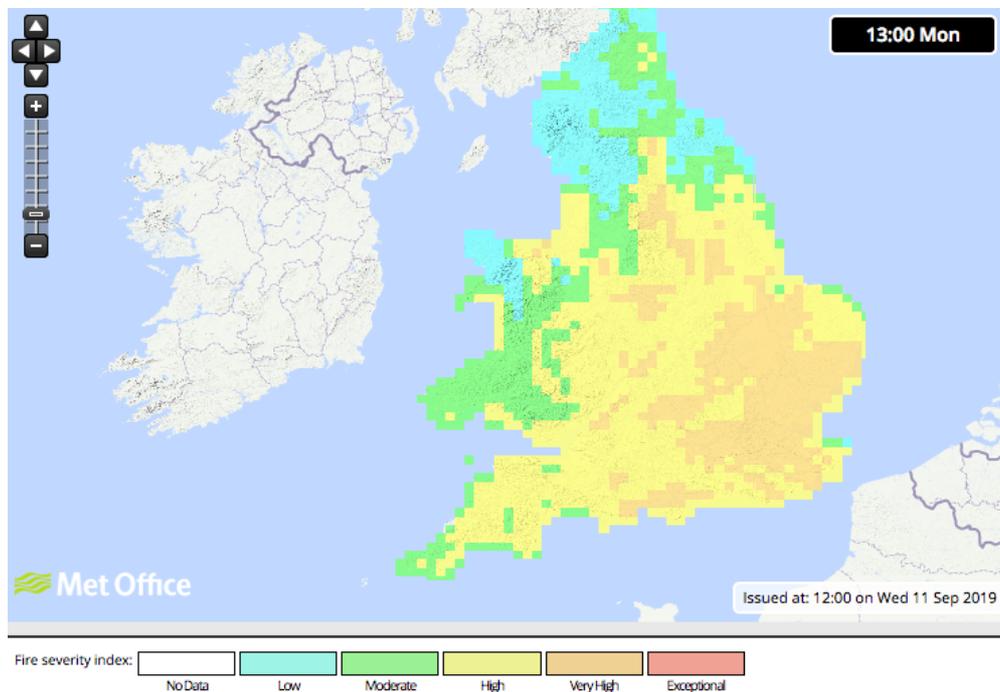


Fig. C1 Met Office ‘Fire Severity’ Index for 18th May 2020. This shows an assessment of how severe a fire could become, if one were to start.

Nearly all UK wildfire ignitions are anthropogenic. Current evidence suggests that there are geographical differences in the sources of ignition. For example, in the case of escaped management burns, this is far more common in the upland areas than lowland areas as burning in these landcover types has been practised for 1000s of years. There is evidence that fire may have been used to clear land since at least Neolithic times and by the late Medieval period burning started to become a common management practice. Currently, fire is used as a management tool as part of grazing and hunting practices, much of which occurs in upland and moorland regions of the UK. Management for red grouse uses burning to create a mosaic of new growth for forage whilst maintaining older stands of heather for cover; burning is also carried out to improve grazing for sheep and deer. Land managers argue that this reduces fuel load and thus prevents intense wildfires. Others counter that prescribed fires can escape to become wildfires, reduce ecological resilience to wildfire, and have negative impacts on key ecosystem services such as biodiversity, carbon stocks and water quality.

A significant common cause in heathland and moorland settings are ‘camp fires’, the exact definition of this is a little vague, but it should be assumed that these are small scale fires initially, that escape their original purpose. It is also difficult to determine if these were deliberately set to start a larger fire, or just carelessly abandoned. The GB Incident Reporting System (IRS) would mostly record these as ‘accidental’ if they are recorded at all. It is often the case that children and young people are a source of both deliberate and such ‘accidental’ ignitions. BBQ’s and military training exercises also feature highly as a cause of ignition in both landscape areas; again, these tend to be recorded as ‘accidental’ in IRS. There is also a significant occurrence of ‘re-ignitions’, which are difficult to classify, and further work is

required in order to correctly allocate them to the original ignition source. Cigarettes are often anecdotally associated with wildfire ignitions, but there is actually very little actual evidence of cigarettes forming a viable ignition source. The UK does not routinely investigate the cause of wildfire ignitions and has no Fire Investigators qualified in this specialist skill. This is an area of concern as it casts significant doubt onto any of the current data sets that record an ignition source. Making studies of social interactions as an ignition source impossible, as such more research is required in this area.

In recent years several large-scale UK wildfire events have led to heightened interest in building an understanding in their behaviour and impacts. Recent analysis of the Fire and Rescue Services (FRS) Incident Reporting System (IRS) by the Forestry Commission England (2019) shows that there were almost 260,000 wildfire incidents attended between 2009/10 and 2016/17 in England alone (an average of 32,000 per year) that burned 37,000 ha and required over 300,000 hours FRS attendance (Forestry Commission England 2019). There are more frequent fires in periods of drought: e.g. in 1995 and 2003. Notably, during April and May 2011, the UK experienced the warmest spring for 100 years. This combined with two public bank holidays, the number of outdoor vegetation fires increased to an average of 374 per day across the UK during the dry April of 2011.

Wildfire activity trends are usually assessed by annual burnt area and/or number of fires exceeding a specified burnt area. These may be determined using satellite earth observation products, aerial photography, or through on-the-ground incident reporting and/or surveying. The European Forest Fire Information System (EFFIS) has one of the longest consistent and continuous records of wildfire activity for the UK, extending back to 2008. As Fig C2a and b shows, 2019 eclipsed the record for the largest burnt area (29,152 ha) and highest number of fires (134); records that were previously held by 2018. Whilst, not reaching the activity of 2019, 2020s saw as many fires as 2018 but slightly less overall burned area. The data for EFFIS come from satellite mapping of burnt area (via the VIIRS and MODIS Satellites). Only fires larger than 30 hectares are reliably mapped due to the limits of the satellite instrument's pixel size. This is a problem for the UK, where many wildfires are small due to the patchwork nature of the countryside. EFFIS state that their system only detects a small fraction of the total number of fires, but that the total burned area is only underestimated by 20–25%, given that a small number of large fires are responsible for most of the burned area.

These data support the findings of the UK's Forestry Commission (Forestry Commission 2019), who found that UK FRS, who report wildfire incidents through their Incident Reporting System (IRS), attend an average of 32,000 wildfire incidents each year, of which the vast majority (>99%) were smaller than one hectare. While the Forestry Commission data also flags 2011 as an important year for wildfires in the UK, the IRS data has yet to be verified for 2018 and 2019, meaning that it is not possible to tell if these years were abnormal from the Fire and Rescue Services perspective.

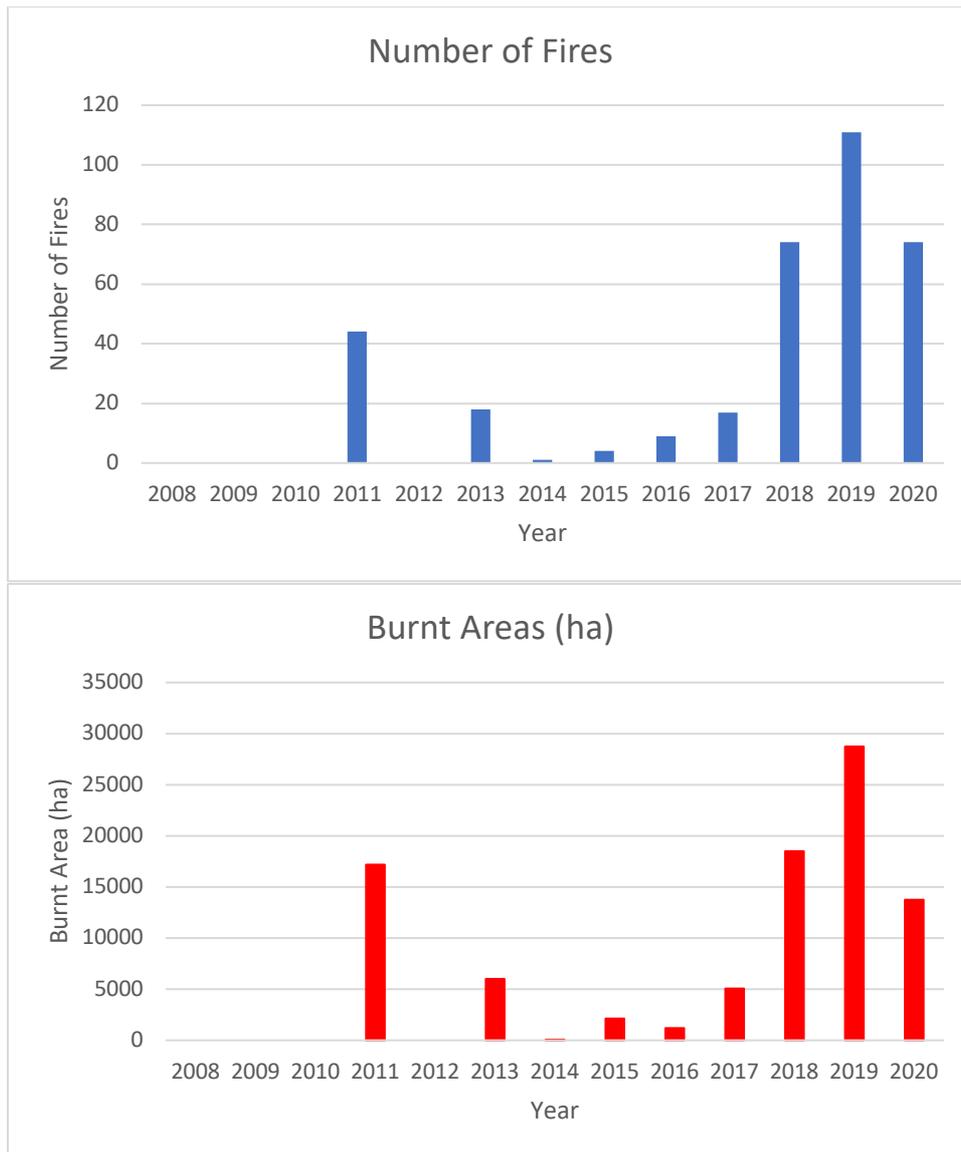


Fig C2 a) (top) number of fires per year in the UK b) burnt are per year in the UK (Source EFFIS)

Seasonality of UK Wildfires

A source of satellite-derived burned area data uses sensors on the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra and Aqua satellites, operated from the USA by the National Aeronautics and Space Administration (NASA). The Collection 6 product MCD64A1 (Giglio et al, 2018) provides global burned area on a 0.004 x 0.004 degrees latitude/longitude grid, equivalent to a spatial resolution of approximately 290m x 470m for the UK

Wildfire occurrence in the UK is also seasonally influenced. Fig. C3a and Fig. C3b show monthly UK fires from MODIS. This indicates that not only does the UK have essentially two fire seasons, early spring (pre heather green up) and summer, but that April 2019 had the highest monthly burned area in the series back to 2003 (Fig. C3b).

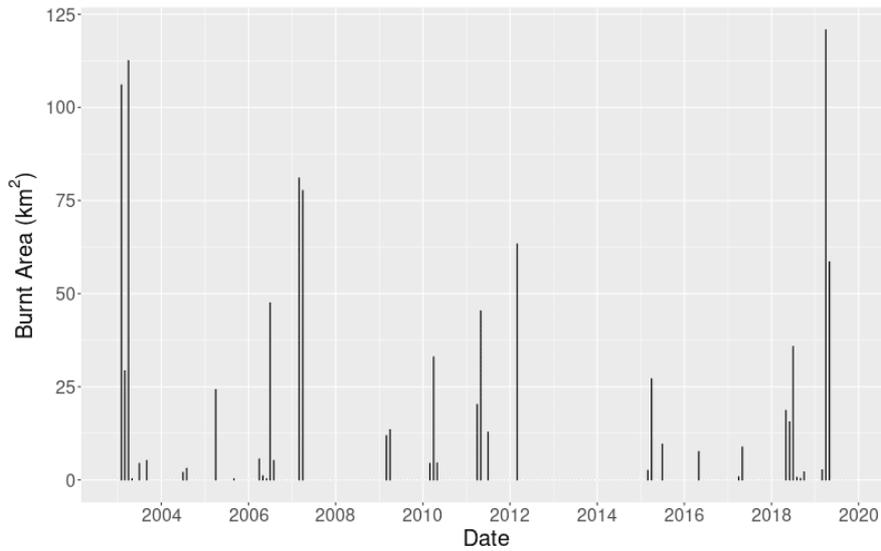


Fig C3a. Monthly UK burned area of large fires from MODIS MDC64A1

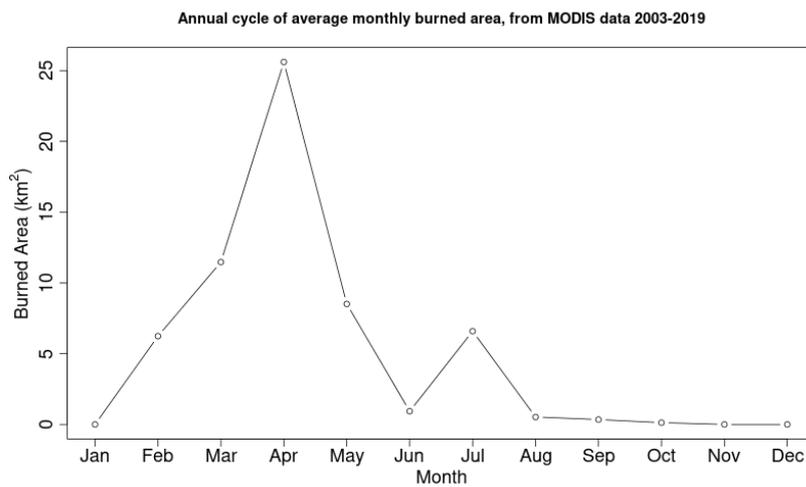


Fig. C3b Monthly burned area from MODIS between 2003-2019

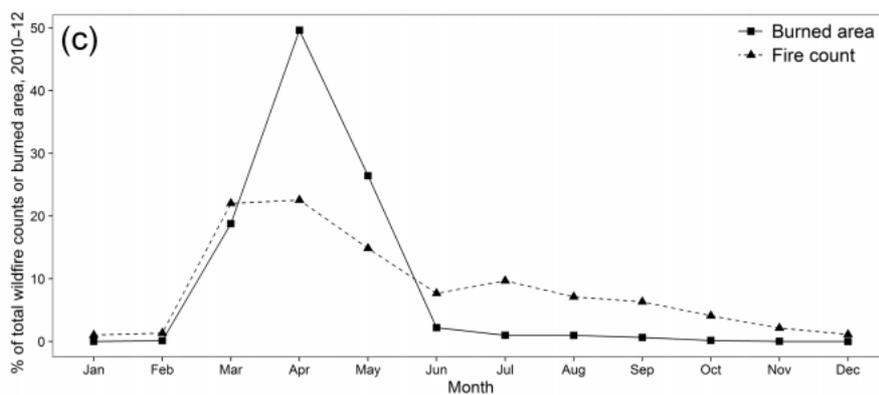


Fig. C4. Total monthly fire counts and burned area between 2010-2012 taken from deJong et al., 2016.

Additionally, in Fig. C4 it can be seen that whilst the spring fire season has the largest total burned area, this is due to a larger number of wildfires, so increased fire frequency begets increased burned area during the spring (i.e., for April 2010-2012 in ~22 fires account for ~ 50 hectares, mean fire size 2.27ha). However, whilst there tend to be fewer summer fires, summer fires tend to be larger, such that a small number of fires attain large, burned areas in

the summer fire season (i.e., for July 2010-2012 ~ 2 fires account for ~10 hectares, mean fire size 5 hectares). This difference between spring and summer fires will place different stresses on Fire and Rescue Services, where large summer fires may need large scale multiregional coordinated efforts by FRS (e.g. Saddleworth Moor, 2018, which totalled ~9000 hectares).

Regional and Land Cover Variations in Fire Proneness in the UK

Figure C5. shows the locations of burned areas in the UK >30ha as monitored by MODIS between 1st March 2018 and 24th March 2020 (Data source EFFIS 24th March 2020) showing that larger fires have broad occurrence across the UK.

The majority of large (>30ha) fires occur in semi-natural vegetated habitats across the UK, although frequent fires occur in a variety of environments from semi-natural habitats to urban patches of grassland. Figure C6, which is based on a Forestry Commission analysis of wildfire statistics, shows the mean frequency and burned area per year for different land cover classes in England over an eight-year period (2009-2017). Fires have occurred most frequently in grasslands and broadleaved woodlands (Fig. C6); however, the greatest burned area occurs in the ‘heathland and bogland’ land cover class and grasslands (Fig. C6).

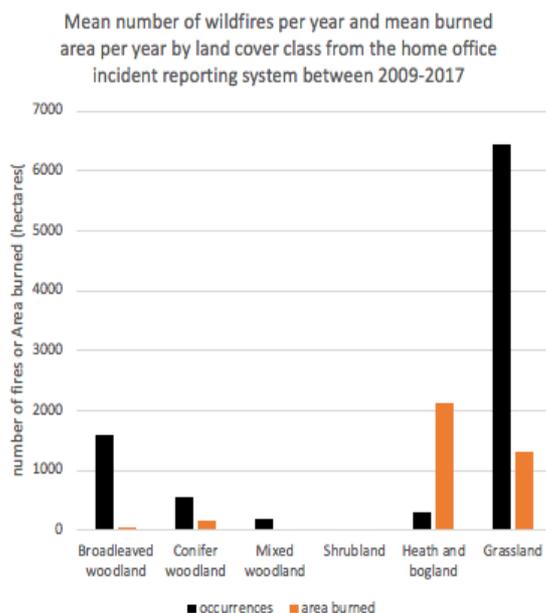
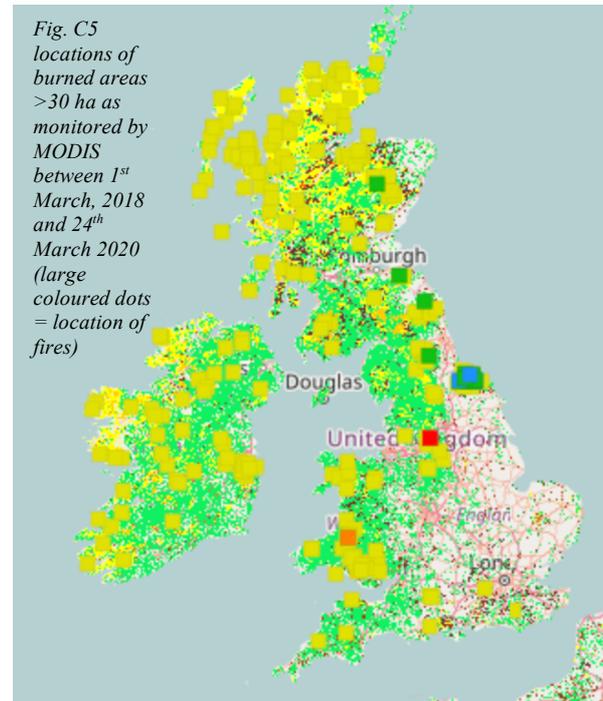


Fig. C6 Trends in fire occurrence and area burned per land cover class

There are two distinct semi-natural fire regimes in the UK; those that occur in woodland habitats, which are frequent but with low burned area and those that occur in open habitats that tend to account for the largest burned areas. Within these land cover classes over 6940 hectares have burned in National Parks and Special Areas of Conservation between 2009 and 2017 and a total of 10,320 hectares in sites of special Scientific Interest, that burned for some 19,000 hours.

Additionally, the largest number of fires occurs in built-up areas and gardens, some 16,000 fires on average per year, although these account for a low average burned area (171 ha/y hectares per year), they pose a significant risk to life, properties and infrastructure assets. As such the range of

land cover classes within the UK pose distinct fire challenges; some that link strongly to risk to human life and property whilst, others link more strongly to land assets and ecological disturbances. It can therefore be demonstrated that the UK has an unusually complex fire regime which incorporates traditional management burning and episodic small and large-scale wildfires. The changing characteristics of both are influenced not only by current processes, such as climate change, but also by historical and current land management activity e.g., via changes in fuel load, type and continuity.

Changing Trends in UK wildfires?

There are no consistent datasets that enable us to establish a ‘climatology’ of wildfires for the UK (i.e. 30-year trends), which makes it difficult to discern whether the recent spike in activity detected by EFFIS is unusual. Although senior officials across UK Fire & Rescue Services acknowledge their experiences of a longer wildfire season, and an increasing spatial scale of wildfires. Fig. C7 shows the MODIS data for the UK and the calculated the total monthly burned area across the UK compared to that from EFFIS (VIIRS). The MODIS data under-reports burned area more than EFFIS as it often fails to map small burns of less than 1 km² but does give realistic results for larger wildfires. The data goes back to 2003, so provides a slightly longer time series than EFFIS. Although it is highly correlated with EFFIS for 2008-2019 ($r^2 = 0.85$), the current trend would be a decreasing one according to MODIS, as the years 2003 and 2007 had large, burned areas, which were not covered in the EFFIS period, that would suggest an increasing trend in wildfires. Hence, the start date of recording can have a large effect on apparent trends over short time periods.

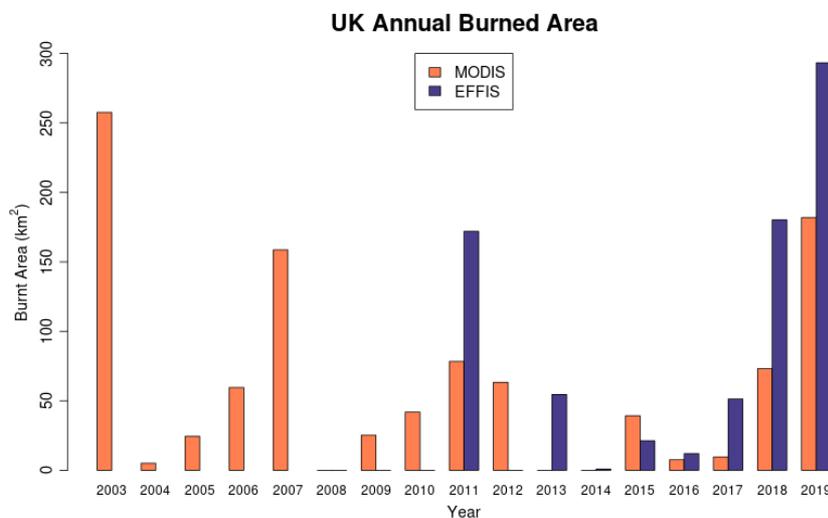


Fig. C7 Comparison of UK annual burned area between 2003 and 2019 from Modis (orange) and EFFIS (blue)

Both EFFIS and MODIS indicate an increase in burned area over the last three years compared to the previous ten years. Fig. C7 also clearly indicates that large, burned areas are periodic, with notably large, burned areas in 2003, 2007, 2011, 2018 and 2019. Hence, increased occurrence of fires that lead to large, burned areas (Fig. C7 and C8) appear to occur on average every 5 years in the UK. It has also been noted that there is a doubling in numbers of fires >30ha since 2013 (which is also the year that wildfires were included for the first time in the National Risk Register).

Overall, the previous three years (2018, 2019 and 2020) have seen the largest number of fires and the largest burned area over the past 10 years (Fig. C8). In 2018, 79 fires accounted for 18,031 hectares burned and in 2019, 137 fires accounted for 29,396 hectares burned. The highest ever recorded burned area in the UK to date. This contrasts to the previous 2011 high of 44 fires and 17,197 hectares burned and a background average for the UK of 25 major fires accounting for 6550 hectares burned. The fire seasons of the last three years (2018, 2019 and 2020) have seen a dramatic increase in both the occurrence of fires and the area burned. It should be noted that all of these figures are an underestimate owing to satellite resolution missing many of the fires in the UK. Hence these numbers are typically for fires >30 hectares per fire.

When the number of fires and burned in the UK are compared with some other northern European countries that have ecosystems at a similar range of latitudes, an interesting pattern in wildfire appears to have arisen over the past few years (Fig. C9). This appears to suggest that conditions conducive to ignition and spread of fires in temperate settings are becoming more common.

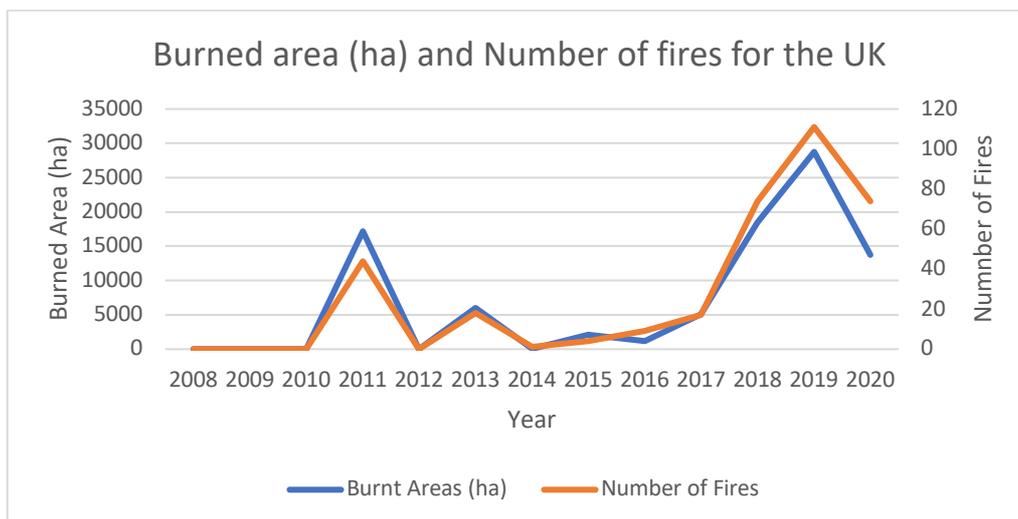
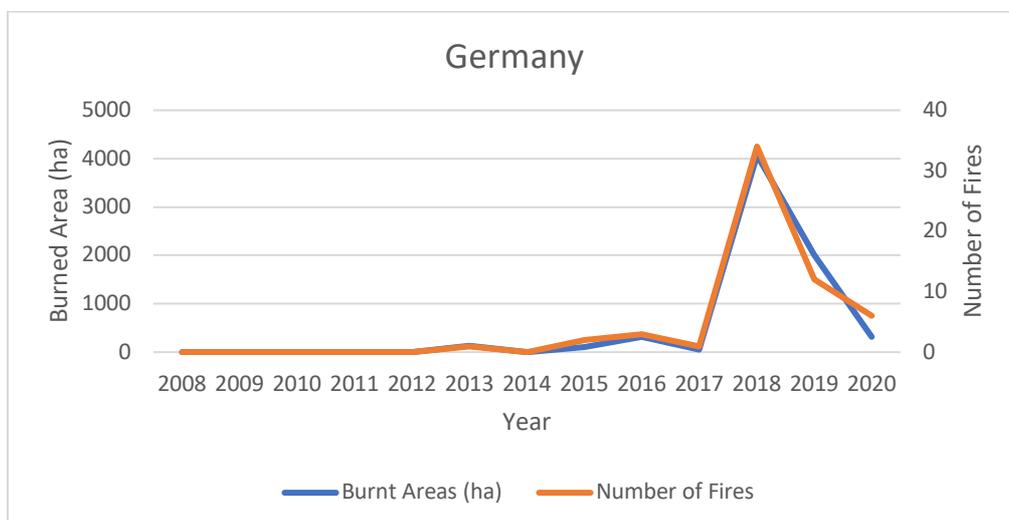


Fig C8. Annual relationship between burned area and fire count from EFFIS for the UK



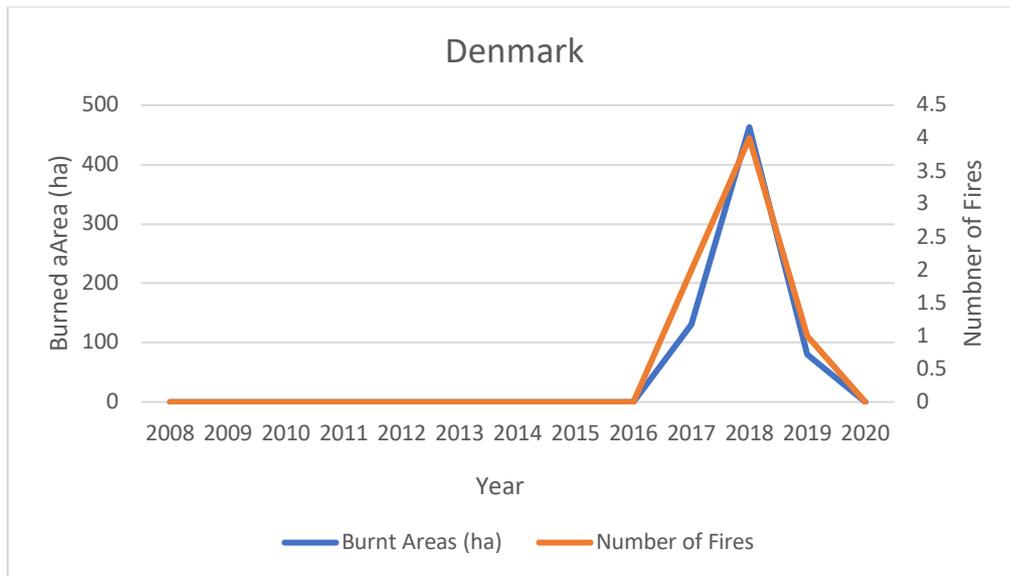


Fig. C9. Annual relationship between burned area and fire count from EFFIS for Germany and Denmark showing a similar increase in fire activity as the UK (Fig. C8) over the past 4 years.

Anthropogenic climate change has led to increases in fire weather indices across the globe. An analysis of recent historic trends in fire weather from 1979 and 2013 revealed that the fire weather season lengthened across 25% of the Earth’s vegetated surface resulting in an overall 19% increase in the number of days conducive to fire (Jolly et al. 2015). A further analysis of global weather data over the period 1979-2019 following a similar approach (Jones et al. 2020), shows that the number of fire weather days has increased globally by 8 days (i.e., a 28.6 % increase). For Australia, for example, the increase has been +9.8 days and Europe +3.6 days.

Reanalysis datasets combine observations from a range of sources with a forecast model to produce a spatially complete and consistent record of global atmospheric circulation. ERA5 is the latest generation reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Its spatial resolution is 0.25° in latitude and longitude (approximately 28 x 15 km over the UK). A range of daily fire weather indices have been calculated by the Copernicus Emergency Managements Service from ERA5 data and are available through the Climate Data Store (2020) for the period from 1979 to the current year. Figure C10 shows the extracted data for the ISI (Initial Spread Index: a numeric rating of the expected rate of fire spread) and FWI (Fire Weather Index: a meteorological based index that links to the chance of wildfire/vegetation fire being started) data over the UK for 1979-2019.

The Figure below (C10a) shows the ISI for spring, expressed as exceedances over a threshold value of 10, averaged annually across the UK for each spring season (March, April and May - MAM). 2011 stands out as having the most frequent severe fire weather in spring, and it was a very warm and dry season for England and Wales. There is no significant trend over the 1979-2019 period. The spring of 2019, which had the highest burned area in the series from 2003, was not exceptional in terms of fire weather across the season and country as a whole. The next Figure (C10b) shows the historical fire weather for the summer season, represented by the percentage of days with FWI exceeding a threshold of 17.35 (Met Office fire danger class 4/5). The episodic nature of summer wildfire is clear, with severe seasons of 1990, 1995 and 2018 standing out, but very little fire danger in many of the other years. Again, there is no significant trend overall.

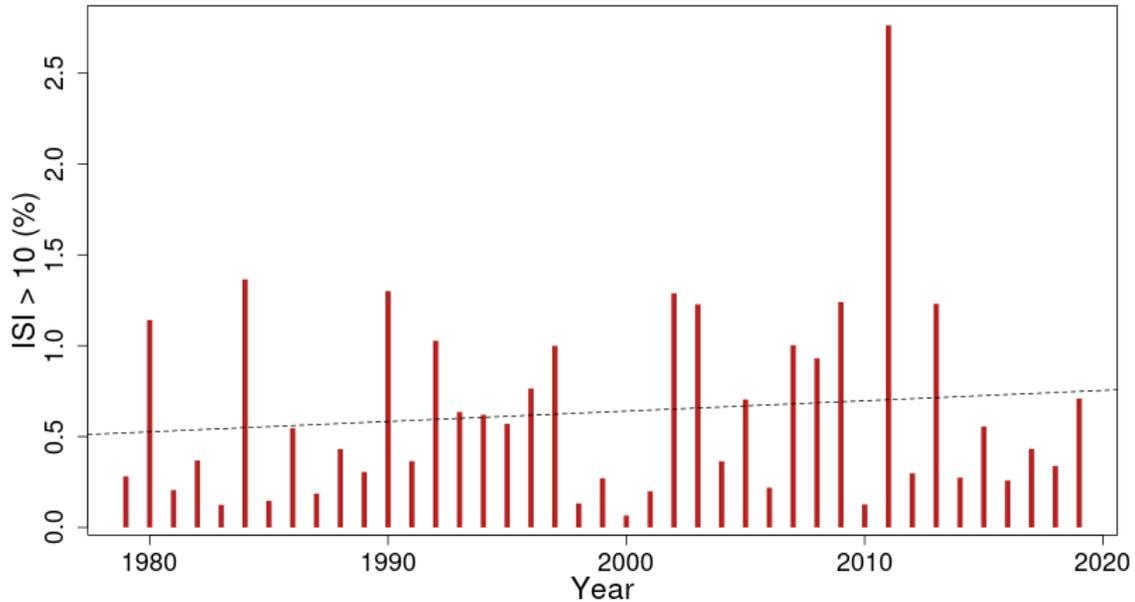


Figure: C10a Annual percentage of spring (MAM) days with Initial Spread Index (ISI) exceeding 10 (level 4/5) averaged over the UK, based on ERA5 reanalysis data for the period 1979-2019. The dashed line shows a linear trend. The Initial Spread Index (ISI) is a numeric rating of the expected rate of fire spread. It combines the effects of wind and the FFMC on rate of spread without the influence of variable quantities of fuel. (The ISI therefore relates best to fire area).

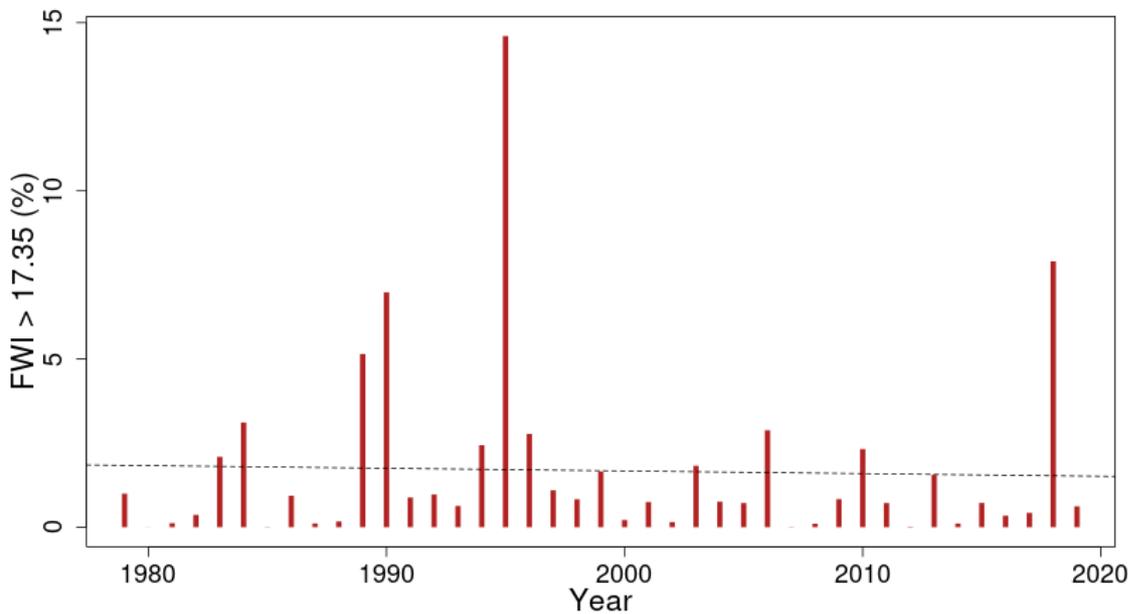


Figure: C10b Annual percentage of summer (JJA) days with Fire Weather Index (FWI) exceeding 17.35 (level 4/5) averaged over the UK, based on ERA5 reanalysis data for the period 1979-2019. The dashed line shows a linear trend. The Fire Weather Index (FWI) combines the ISI (initial spread index = expected rate of fire spread) and the BUI (build up index = total amount of fuel available for combustion) so is a numeric rating linked to fire intensity. It is suitable as a general index of fire danger.

D) Predictions for Future Wildfire activity

Changes to UK wildfire activity may be explained by a combination of fuel (load and type), weather, and ignitions. Climate change influences all three of these factors. Predicted warmer wetter winters (UKCIP, 2018) and the resulting longer growing season will see a greater abundance of vegetation. While more frequent and longer-lasting heatwaves will lead to drier vegetation, increasing the amount of fuel available to burn. Warmer summers are likely to lead to more people participating in outdoor recreation activities, a major source of ignitions. Researchers have modelled these climate change impacts for the Peak District of the UK to find that a combination of higher temperatures, and a rise in the risk of ignition due to increased recreation, will likely lead to more summer wildfires towards the end of this century (Albertson, 2010). Statistics from the UK Met Office report on Climate Extremes (UK Met Office, 2018) suggest that the UK is already feeling the effects of climate change, with the average length of a warm spell increasing from 5.3 days (1961–1990) to 13.2 days (2008–2017), with the rain falling during wet days and extremely wet days increasing by 4% and 17% over the same period, respectively. These changes may well be part of the explanation for the 2018 and 2019 fire seasons.

Future projections of Fire Danger Classes in the UK have recently been analysed (Perry et al., 2021) using the UKCP18 climate model. Daily values of air temperature, relative humidity, wind speed and precipitation have been used to compute daily values of the Fire Weather Index (FWI) and its sub-indices out to 2080. This has used a regional model which has a 12 km spatial resolution over the UK and is comprised of a perturbed parameter ensemble of 12 members (PPE-12). This allows uncertainty in the model parameters to be explored and provides a range of possible outcomes that can reveal the potential for extreme fire weather conditions. However, the ensemble does not cover the full range of uncertainty, and it is derived from a model which samples the warmer end of the future response range due to its higher climate sensitivity to greenhouse gases.

The change in climate projected by models in UKCP18 is strongly dependent on future global greenhouse gas emissions. UKCP18 uses scenarios for future greenhouse gases called the representative concentration pathways (RCPs) which make assumptions around future population, economic development, and any mitigation of greenhouse gas emissions towards international targets. The 12 km projections are only available for the RCP8.5 scenario, which is at the upper end of emissions concentrations. The combination of use of a high sensitivity model and a high concentration pathway means that the results presented are at the upper end of possible future outcomes. All climate models exhibit differences between model results and observations. Bias adjustment techniques can be used to adjust for these differences, but this has not yet been applied, and the work has not yet been peer reviewed, so the results should be interpreted with care. For example, the historical and projected future evolution of fire weather indices from the late 20th century to the late 21st century is shown in Figure D1a (FWI for the spring) and Figure D1b (FWI for the summer). The UKCP18 models currently suggest that the frequency of severe fire danger is projected to undergo a large increase in summer and a slight increase in spring. Each figure shows the 12 individual ensemble members, their mean and the 10th–90th percentile range, compared to the ERA5 data until 2019. As the ensemble consists of twelve members, there are only two runs with fewer severe-fire-danger days than the value indicated by the 10th percentile, and only two runs with more severe-fire-danger days than the value indicated by the 90th percentile.

The ERA5 data (orange) however, indicate that the occurrence of very high fire weather index in spring are currently underestimated in the UKCP18 models. Whilst, for summer, the modelled very high fire weather index is mostly within the ensemble range (compare orange line with other lines). This indicates that the UKCP18 models likely underestimate the fire risk in spring suggesting that their future predictions may produce considerable underestimates of FWI in the spring months. Hence currently, future years, appear to show only a slight increase in dangerous FWI in spring, despite the risk likely being much greater. The summer predictions, which appear correct show a rising trend in FWI into the future that appears to accelerate considerably after 2040. By the 2060's, a normal summer is similar to historical extreme years such as 1995. Particularly extreme summers are projected to have much more extensive occurrence of severe fire weather spatially across the UK and temporally throughout the season.

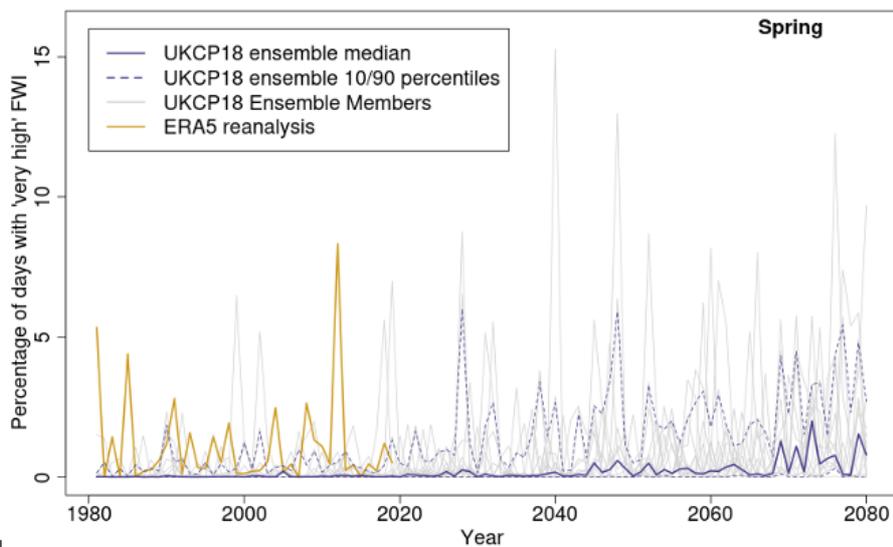


Figure D1a: Percentage of spring (March-April-May) days per year with 'very high' fire danger ($FWI > 12.58$), averaged across the UK. UKCP18 ensemble members (grey), their median and 10th/90th percentiles (blue) and the ERA5 reanalysis data (orange).

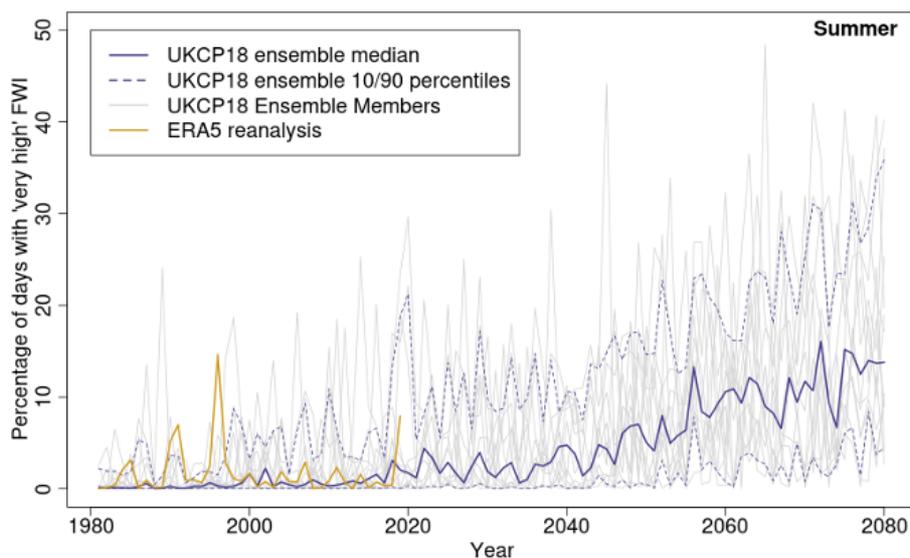


Figure D1b: Percentage of summer (June-July-August) days per year with 'very high' fire danger ($FWI > 17.35$), averaged across the UK. UKCP18 ensemble members (grey), their median and 10th/90th percentiles (blue) and the ERA5 reanalysis data (orange).

Figure D2 shows the monthly predictions for the percentage of days likely to experience very high fire weather index based on either 2°C global warming or 4°C global warming compared to the reference period of 1981-2010. Throughout the reference period the percentage of days with very high FWI is 10% or less, peaking during July and August. However, based on future global warming projections this may rise to ~27% or has high as 55% for summer days according to 2°C or 4°C warming respectively.

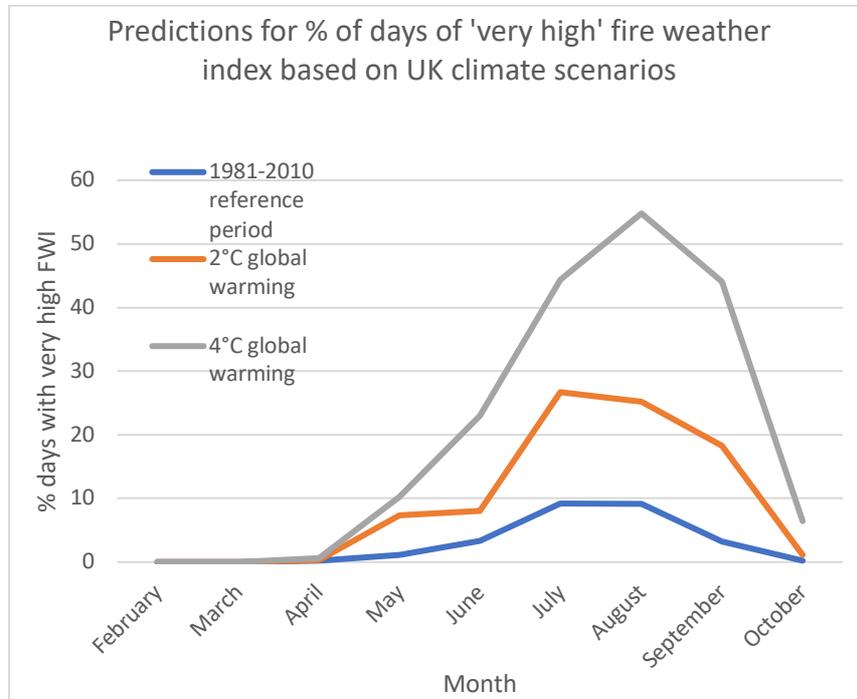


Fig. D2: Monthly projected percentage of days with 'very high' FWI according to two global warming scenarios. Plotted from data gathered from the UK Met Office.

The spatial distribution of the occurrence of fire weather prediction are shown in Figures D3 and D4 Initial Spread Index (ISI) is show for spring (Fig. D3) and FWI is shown for summer (Fig. D4). The future periods of 2026-2035 and 2060 to 2069 are representative of global warming levels of 2°C and 4°C respectively. In spring, where the spread index is the most important metric, high ISI is most frequent over most of central and southern England, coastal parts of northern England, Scotland and Wales. There is little change to the spatial pattern in the future periods, but a slight increase in the number of days experiencing higher ISI is observed. In summer, very high FWI is mainly concentrated in central and southern England, but these areas are predicted to expand and intensify considerably in the future periods, with large areas exceeding 30% of days with severe fire danger by the 4°C global warming level.

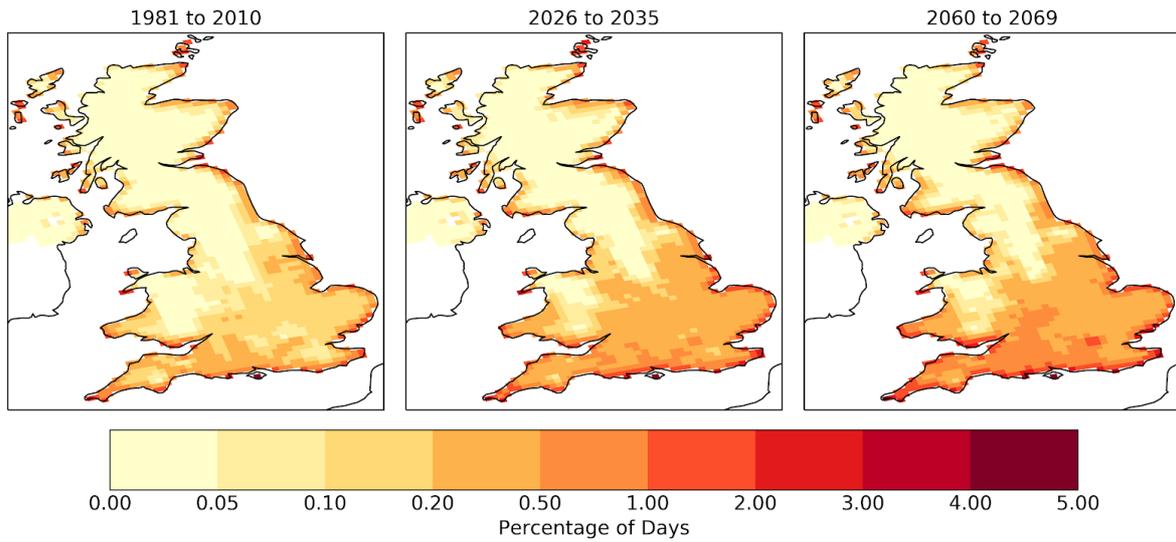


Figure D3: Annual occurrence (% of days) with Initial Spread Index (ISI) > 7.5 during spring (MAM) from the UKCP18 12km regional model averaged over the 12 ensemble members for a) 1981-2010 baseline period b) 2026-2035 (2 degC global warming level) and c) 2060-2069 (4 degC global warming level).

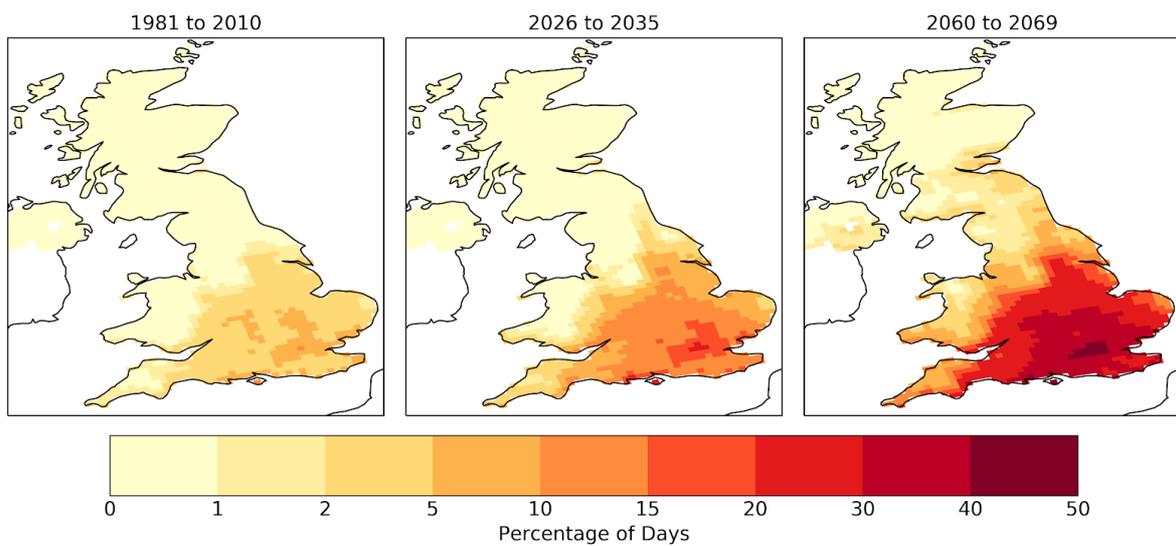


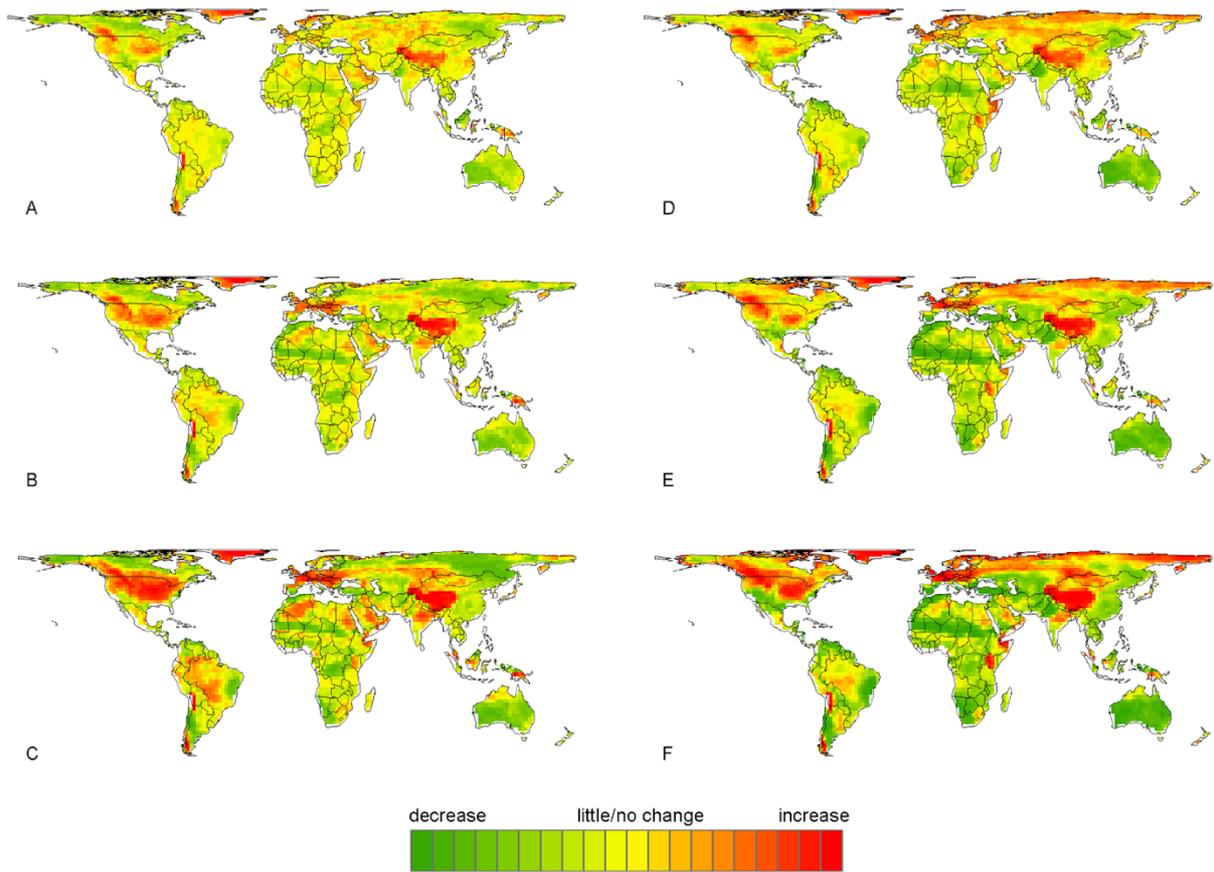
Figure D4: Annual occurrence (% of days) with Fire Weather Index (FWI) > 17.35 (Fire Danger Class 4/5) during summer (JJA) from the UKCP18 12km regional model averaged over the 12 ensemble members for a) 1981-2010 baseline period b) 2026-2035 (2 degC global warming level) and c) 2060-2069 (4 degC global warming level).

An additional study looked at the effect of climate change on indicators of fire danger in the UK (Arnell et al., 2021). Arnell et al., (2021) also use the UKCP18 climate projections, the ERA5 reanalysis (Copernicus climate change service 2017) and take the RCP2.6 and 8.5 climate projections for the 2050s and 2100 to predict aspects of FWI using the Met Office Fire Severity Index (MOFSI) for different regions in the UK (14 regions of the UK are discussed and data explored). All predictions suggest a very large increase in fire weather derived indices across the UK. The greatest increases are forecast in the South East and Central Regions of England. In southern England the period between 1981 and 2010 is indicated to have experienced on average 20 days per year of very high FWIs, this is predicted to rise from here on up to 70 days per year by the 2050s and 111 by the 2080s (Arnell et al., 2021). An increase is also seen in the north of England and in Scotland, but the increase in the number of days experience very high FWIs is delayed beginning later from 2040 onwards. The risk of wildfires in the south becomes greater still from the 2050s onwards where there will be days that reach MOFSI's 'exceptional' fire weather category.

These changes in aspects of the MOFSI FWIs are driven by coupled variations in meteorological conditions. Where it has been suggested the variations in Fine Fuel Moisture Code (FFMC)(i.e. fuel moisture) is mostly driven by increased temperature and its associated reduction in relative humidity (approximate 50:50 ratio). This also has a regional variation where relative humidity plays a more significant role in the decrease in FFMC in the south than the north. Variations in rainfall itself appears to have limited influence on FFMC. The likelihood of fire spread, known as Initial Spread Index (ISI) is more influenced by rainfall variations than FFMC but it is the decrease in relative humidity that serves as a primary driver of enhancement of the number of days of high ISI. Hence the main drivers of the increase in the number of very high FWIs are driven by increased temperature and decreased relative humidity.

Of significant interest is the fact that the Arnell et al., (2021) study highlights the importance of reducing emissions and how this would interact with FWIs and therefore future fire risk. It states that if emissions are reduced to that which would lead to a 2°C global mean temperature then this would reduce the number of days of very high FWIs, particularly in the north compared to the current day where many of the countries peat carbon stocks are located.

Other studies whilst, not focussing on the UK, but that include the UK, also make similar suggestions. In one of the few studies of the global distribution of increases/decreases in wildfire probability (fire proneness), Krawchuk et al. (2009) found a progressive increase in wildfire probability for the whole of the UK through the 21st century (see Fig. D6).



Fig, D6: Changes in the global distribution of fire-prone pixels under a mid-high emissions scenario. Maps on the left-hand side include modelled changes in climate and vegetation biomass; while maps on the right-hand side only include changes in climate with no changes in vegetation biomass. The top row are projections for the period 2010-2039; the middle row are projections for 2040-2069; and the bottom row are projections for 2070-2099
(adapted from Krawchuk et al., 2009)

A modelling inter-comparison study (Wu et al., 2015) focussed on climate and CO₂ driven changes in burned area across Europe based on two RCP scenarios. Figure D7 shows sensitivity of burned area in Europe to climate change, atmospheric CO₂ levels, and demography and compares two fire-vegetation models.

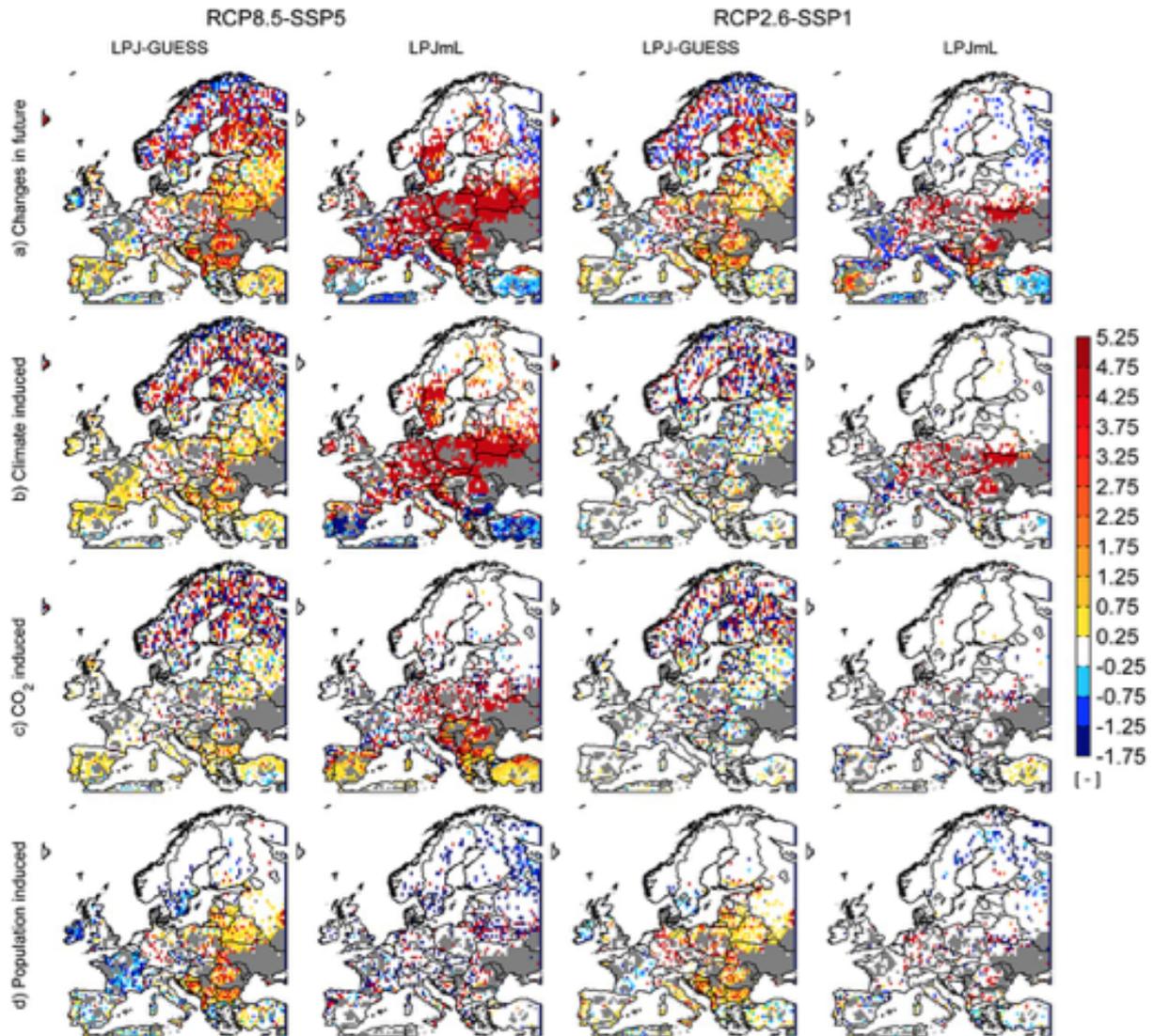
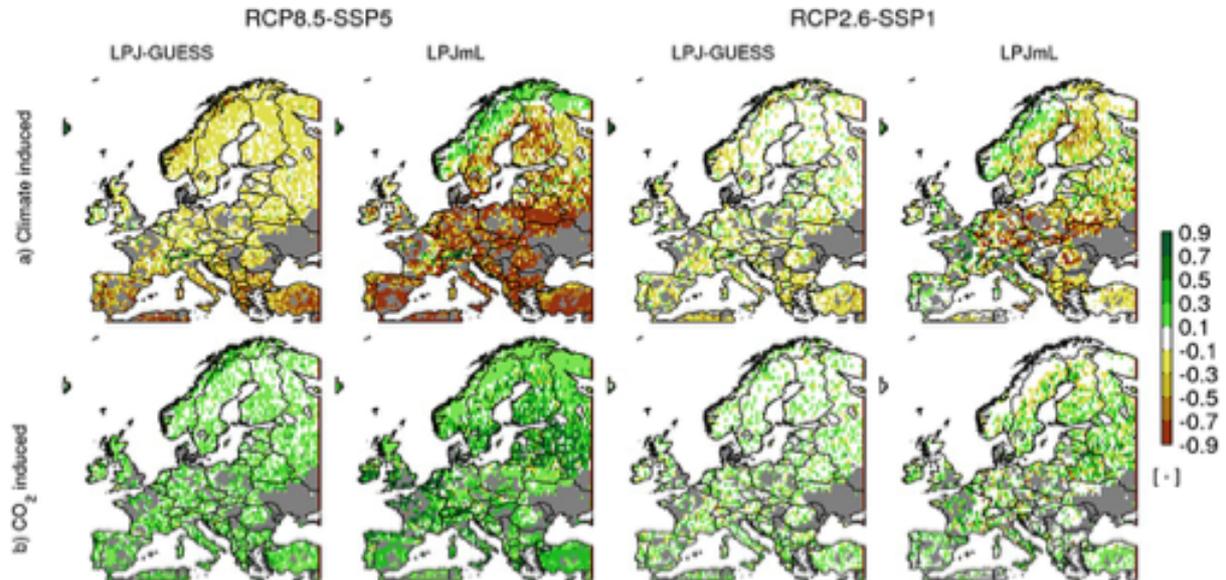


Fig. D7 showing - Changes in mean annual burned fraction (BF) in MPI-ESM-LR simulations related to present date. (a) Relative changes between future (2081–2100) and present date (1981–2000) in experiments FUL_EFF ($BF_{future}/BF_{present-day} - 1$); (b to d) Relative factorial effect (RFE, equation and table) for annual burned area fraction in future. Only significant changes ($p < 0.05$) are presented using Mann-Whitney U test. Areas with no change or nonsignificant change are in white. Areas with greater than 50% agricultural land were excluded (grey). Taken from Wu et al., 2015.

Overall changes in mean burned fraction (a) for the UK are greatest under RCP8.5-SSP5 with more moderate changes under RCP2.6-SSP1. It is clear that although this model is not UK focussed that increases in burned fraction in the UK are to be expected in the next 60 years. The difference between models (LPJ-Guess vs LPJmL) are due to differences in their simulated vegetation composition and fuel load. See Fig. D8.



*Fig. D8- Relative factorial effects for fuel load represented as the sum of aboveground biomass and litter due to changes in climate and atmospheric CO₂ concentration. Results are from MPI-ESM-LR, only significant changes ($p < 0.05$) between *FUL_EFF* and correspondent factorial experiments in future (2081–2100) are presented using Mann-Whitney U test. Areas with no change or nonsignificant change are in white. Areas with greater than 50% agricultural land were excluded (grey). Taken from Wu et al., 2015.*

Some regions of the UK see a decrease in fuel load (~10% in Scotland) whilst, others see an increase of up to 30%, particularly in Wales, North Yorkshire Moors, Peak District, South Downs and Higher Weald. Despite variations in fuel load the climatic driver of fire appears to override the fuel load driven shifts to suggest larger mean burned fractions for the UK by 2100. Interestingly in some parts of the UK (Scotland, the SW, the midlands and areas in the south and south west) there is a loss of grassy fuels predicted and increase in woody fuels (Fig. D9). Whilst this study is not UK focussed it indicates that there will be both changes in fuel and climate driven fire for the UK by 2100, such that both will need considering in more detail looking forward.

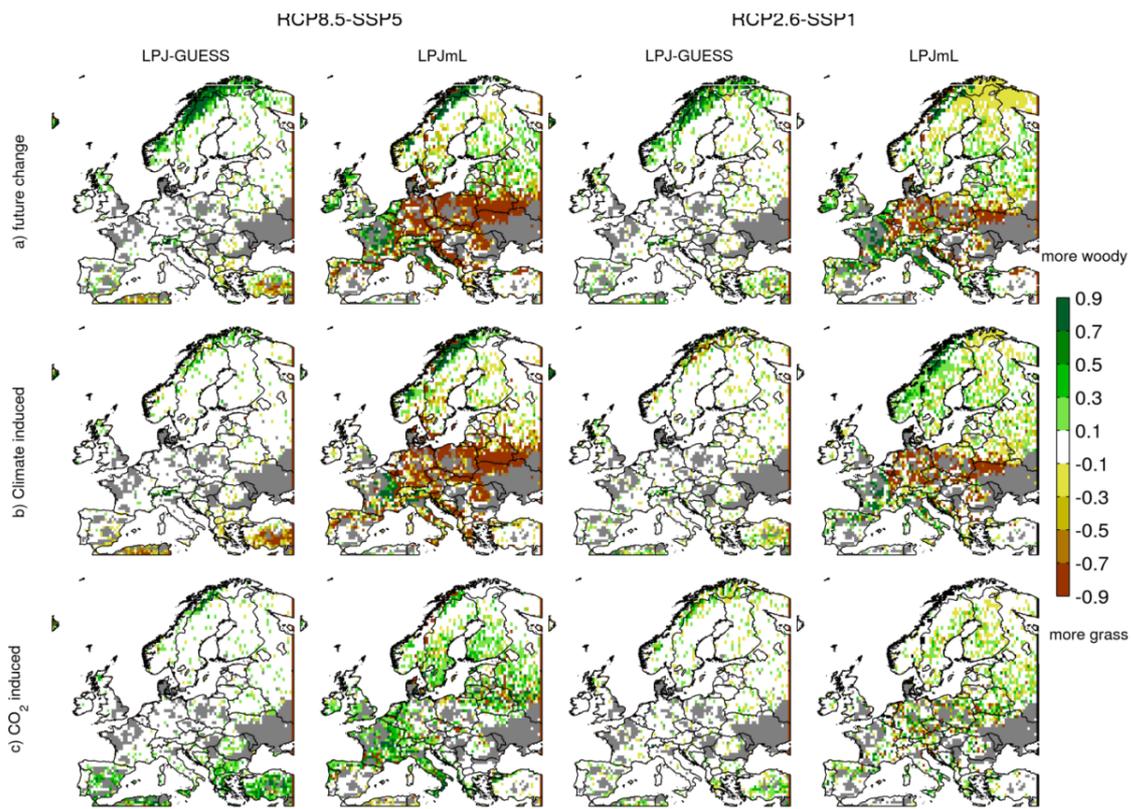


Fig D9 showing changes in woody-grass ratio a) changes between future (2081-2100) and present-date (1981-2000) b) differences for future c) CO₂ induced changes. Area with >50% agricultural land was excluded (grey). Taken from Wu et al., 2015.

Changes to Ignitions in the Future

Open landscapes attract visitors, and people are the primary cause of wildfires at present. These ignitions are either via accident e.g. BBQs in open areas, or via arson as examples. While our population continues to grow our open habitats will be put under ever increasing pressure. This will inevitably lead to an increase in ignitions, particularly as our climate creates suitable conditions more frequently. Natural ignition sources such as dry lightning may also increase as our climate changes. In 2018, the UK saw its first recorded wildfire start from lightning, although there are several other anecdotal observations, is this the start of a new trend?

The UK's Flammable Peatlands and Climatic Change

The wildfire regime within the UK varies between different land cover types, notably in terms of fire frequency and burn area (Forestry Commission England, 2019). Understanding the risks of wildfire under future climatic conditions across the diversity of UK land covers is of critical importance. However, we make specific mention here to the importance of peatland ecosystems. Wildfire within peatlands has a key impact on ecosystem service provision (Davies et al., 2013; Emmerton et al., 2020, Worrall et al., 2011), like other land cover types. However, these ecosystems are deemed worthy of special mention because of the scale of wildfires, both in space and time, within peatland ecosystems and their direct feedback to changing climatic conditions. Wildfires within Mountain, Heath and Bogs account for

approximately 1% of UK wildfires (Forestry Commission England, 2019). However, between 2009/10 and 2016/17 they accounted for between 4 and 82% of the area burned within the UK (Forestry Commission England, 2019). This included notable large fires in recent years such as the ~1000 ha Saddleworth Moor fire in 2018 and the ~16,000 ha Knockando wildfire in 2019. Whilst fire spread within peatlands is dominated by flaming combustion of surface fuels (Santoso et al., 2019), severe peatlands wildfires are also characterised by smouldering combustion of the peat soils (Turetsky et al., 2015); combustion of a proportion of the organic matter that has taken place over centuries. Globally such smouldering combustion can continue for months (Page and Hooijer 2016), extending the period of the wildfire event. Within the UK, such smouldering has been observed to continue from at least weeks, and is extremely challenging for fire and rescue services to successfully extinguish; taking up substantial resources if this is attempted (Davies et al., 2013). This incomplete combustion of peat is responsible for poor air quality (Hu et al., 2018) and has the potential to burn legacy carbon deposits (Turetsky et al., 2015). Unlike for example grass fires that burn the carbon accumulated within the vegetation between fire events with no net carbon loss over fire cycles, peatland fires have the potential to burn carbon stocks that were locked within the peat that have accumulated over many fire cycles. Thus, the carbon stock will not be sequestered on a timescale relevant to changing climatic conditions and the wildfire event will act as a net carbon source (Ingram et al., 2019).

Drier conditions associated with projected increases air temperatures and associated increases in evapotranspiration have the potential increase fire intensity and spread within Calluna (Heather) dominated peatlands (Davies & Legg 2011 and Davies & Legg, 2016). However, the extent to which inter annual variation in fire behaviour will be replicated over changing climatic conditions and the magnitude of such responses across the diversity of vegetation communities of UK peatlands is unknown. Further, warmer climates could in some isolated conditions even reduce the rate of spread and extreme fire behaviour, where physiological drought in spring result of frozen soils and may reduce the moisture content of live biomass (Davies et al. 2010). These impacts will be exacerbated and/or mitigated by disturbances and landscape management practises. Long term disturbance to the peat through atmospheric deposition, drainage, burning and grazing each modify to composition of the peat and will likely modify the fire risk. Notably, drainage has been shown to increase the vulnerability of the peat to wildfire (Granath et al. 2016; Turetsky et al. 2014). Increases in peat bulk density and reductions in the specific yield of the peat can exacerbate the impact of drying (Kettridge et al., 2015) and produce peat profiles that under drought conditions are susceptible to sustained and deep smouldering combustion (Prat-Guitart et al., 2016). Rewetting peatlands raises the water table and should protect peat carbon stocks. However, this is only likely if high water table positions are retained even during periods of drying when summer fires will likely occur (de Jong et al., 2016) or the development of protective moss layer results (Deame et al., 2020). Despite the potential impact of fire severity, raising the water table likely has minimal directly influence on ignitions and fire spread, but instead influences fire risk through the modification to the vegetation composition of the peatland (Tuittila et al., 2000).

The high water table positions that dominate undisturbed peatlands means that the vegetation composition of peatlands has been considered to be potentially susceptible to comparatively small modifications in the peat moisture contents (Frolking et al., 2010) potentially induced as a result of changing climatic conditions. A change in vegetation species composition (Robroek et al., 2017) and density would be expected to directly influence wildfire risk, with fire severity varying by habitat/vegetation type (Glaves et al., 2020). However, the impact of the interconnected interactions of changing community assemblages in response to changing

conditions, the magnitude, timing and spatial extent of such changes, and their influence on wild fire risk is not known. Again, any changes will be severely impacted by the management decisions that will modify the vegetation composition, age, density and medium and large scale structure of peatland fuels (e.g. Heather). Whilst simply the reduction in fuel density would be expected to reduce fire intensity and severity, the interaction of fuel density, with medium term transitions in community assemblages and associated flammability, moisture dynamics and ignition potential must be considered. As a result, there is a need to determine how managed burning, grazing and mowing modify wildfire risk under future climates.

For a detailed review of wildfire in peatlands within the UK we refer you to the 2020 Natural England review (Glaves et al., 2020).

E) Looking forward: Building Wildfire Resilience in the Face of Climatic Change

Natural Environment and Assets: Management of the Landscape and Fuel in Response to Enhanced UK Wildfire Risk

Currently most conservation legislation in the UK is aimed at the protection of species and habitats, many of which are open habitats such as lowland, upland heath, grasslands and moorlands (Forestry Commission England, 2019; Wentworth and Shotter, 2019). These habitats are often in landscapes containing AONB (Area of Outstanding Natural Beauty) or National Parks, often containing sites within them that are designated as SSSI (Sites of Special Scientific Interest), SPA (Special Protection Areas), Special Areas of Conservation (SAC) or Ramsar sites in regard to either rare flora or fauna. These open habitat types are also amongst the UK's most fire prone ecosystems. As we move forward in the era of climate change mitigation we can sometimes be faced with seemingly conflicting agendas in terms of fire and ecosystem management challenges in regard to conservation and maintenance of existing habitats and during transition between habitat types. Conservation and existing ecosystem maintenance agendas will need to be set against a) climate driven vegetation shifts where, for example, Fig. D9 predicts that climate change could naturally tend towards increasing woody fuels at the expense of grassy fuels in some parts of the UK (Scotland) (Wu et al., 2015) whilst in others approx. a 30% increase in fuel loads is predicted (Wales, North York's Moors, Peak District, South Downs and Higher Weald)(Wu et al., 2015) and c) carbon capture initiatives/mitigation strategies, such as afforestation (see review by Sloan et al., 2018) and re-wilding schemes (Perino et al., 2019). All such schemes, be it for conservation of existing ecosystem or 'zero carbon' initiatives, require consideration of the relationship between landscape level changes and wildfire and complete analyses of both short and long-term impacts on wildfires and their feedbacks. As examples, afforestation schemes (using native spruce) enhanced the severity of peat burning in the Fort McMurray River wildfire, Canada (Wilkinson et al., 2018), whilst others have highlighted that without proper land management afforestation can enhance wildfire activity in some ecosystems (e.g., native Mediterranean Pine species) (Cervera et al., 2016). As Sloan et al. (2018) outline 'A large body of research on peatland forestry exists, particularly from naturally forested fen peatlands in Fennoscandia and Russia, but the different conditions in the UK mean that results are not directly transferable. Data on the responses of UK peat bogs to afforestation are required to address this shortfall.'

If the Wu et al., (2015) predictions are correct and grassy fuels in some areas of the UK become replaced with more woody fuels then based on Fig. D9 (this document) a shift to broadleaved ecosystems might decrease burned area but would appear to increase fire occurrence in some regions. However, management approaches, including decisions about which species are allowed to colonise given areas, will clearly influence this flammability. More significant is the predicted 30% increase in fuel load in many fire prone landscapes (Wu et al., 2015 and Fig. D8 herein). More research is therefore required that is tailored to UK ecosystems because, as this CCRA3 summary indicates, there will be an increase in the number of days that carry suitable fire weather (e.g., Fig. D3 and D4) and that climate-driven fuels shifts (fuel load and/or fuel type) will tend towards enhancing fire (Figs. D6 to D9, Krawchuk et al., 2009; Wu et al., 2015). Therefore, whatever the land management agenda the potential alteration to wildfire risk must be considered, understood and managed.

Fires cannot exist without fuel. Therefore, the type, load and moisture of fuels are aspects of the environment that we can consider when attempting to adapt and manage the UK semi-natural landscape when it comes to wildfires. In the following sections, we outline some of the approaches that are being, or can be, used to manage fuel in the UK and during wildfire incidents.

Habitat and Fuel Management using Mechanical and Manual Means

Mechanical fuel treatments are machine-based activities that are used to alter the size and arrangement of vegetation biomass by cutting through stems, trunks and shrubby components and creating smaller fragments or by removing these cut parts from the site (bundling, bailing, biomass harvesting etc.) for disposal or utilization (Mitchell and Smidt, 2019).

A variety of mechanical fuel treatment options are available for managing vegetation and fuel loads. Many treatments are carried out independent of whether there are perceived links to wildfire risk. In fact, most habitat management in the UK is undertaken by mechanical means, with approximately 4% of the UK's total workforce being employed in the environmental and land management sector (LANTRA, 2010). In regard to fuel management, vegetation and timber may be harvested by bailing and bundling and the size fraction altered by mastication (Windell and Bradshaw 2000; Rummer 2010). In some cases, the products produced can become marketable products themselves (Mitchell and Smidt, 2019). Although where mastication is used no material is removed from the site, rather the fuel structure is altered, which may or may not influence fire risk (Marino et al., 2012). The types of manual and mechanical land management practices ongoing in the UK currently include:

- Agricultural ploughing, seed drilling, crop sprayers and harvesters.
- Forestry thinning and harvesting using either purpose built or tractor-based tree harvesters and forwarders as well as site preparation mulchers and excavator-based planting. Additionally, hand tools are used including chainsaws, clearing saws.
- Game management using All Terrain Vehicles, Off Road Vehicles, petrol backpack blowers, high-pressure pumps etc.
- Environmental management to harvest heather and cut rides and tracks.
- Estate management using tractors, mowers, excavators, sprayers, front loaders etc.
- Land clearance and preparation using pesticides. This is normally only over small areas, but occasionally can be used at much larger scale.
- Chopping, scraping, subsoiling and turf cutting to reduce nutrients.

Forestry guidance in the UK has been working towards providing wildfire mitigation for at least a decade. Here the aim has been to prevent the build-up of fuel across entire individual sites or if not financial or practically viable, at strategic locations identified by wildfire management planning (Forestry Commission, 2014). This can include the use of timber thinning and harvesting to remove timber and disturb surface fuels to improve resilience (Forestry Commission, 2014), environmental management to remove heather, gorse and other materials, and cutting of grass or corn during cropping and harvest. Additionally, forestry has begun using different planting regimes, planting belts of less fire prone vegetation around more flammable units, and utilising firebreaks and defensible zones around infrastructure to provide wildfire adaptation and prevent large fire spread (Forestry Commission, 2014).

A positive of mechanical fuel management, including creating fuel breaks or containment lines, is that this practice is not subject to the burning season. Neither is the bailing of heather. Although it should be noted that any cutting or bailing operations may be subject to other legal controls such as the Wildlife and Countryside Act. In upland or heathland environments cutting of heather can be used for both fuel management needs and to improve grazing. However, this is dependent on a number of factors including access; not all areas are accessible to large mowing equipment for example. Moreover, mechanical mowing can damage important archaeological sites and some habitats exposing the soil which can destabilise some habitats. For example, practices such as heather turf cutting typically remove around 10cm of soil and duff that lies beneath the surface heather. Additionally, there may be new opportunities to use cut biomass to produce energy (Worrall and Clay, 2014) in certain areas. Particularly using heather where management burning has been common this could be swapped for cutting and bailing and used as an energy crop. Worrall and Clay (2014) modelled that UK could have a potential energy production of up to 40.7PK yr⁻¹ saving up to -2061 ktonnes CO_{2eq} yr⁻¹.

Management of fuels around homes and assets should primarily aim to break up fuel continuity and to increase the fuel moisture content close to the home or asset. Ideally the structure of the fuel will lead to a decrease in fire intensity as any wildfire approaches the asset at risk [NFPA 2008]. Indeed, communities that live adjacent to fire prone UK landscapes are being empowered to manage fuel around them under the recently started UK Firewise scheme, linked to that in the USA. Whilst, the Firewise approach is not widely known about in the UK at least three communities have recently adopted the scheme along with support from local fire and rescue services (e.g. <https://www.dwfire.org.uk/safety/heath-fires-and-countryside-safety/firewise/>) and this is likely to prove to be an invaluable adaptation tool to protect our Rural Urban Interface (RUI) and deserves governmental funding.

Habitat and Fuel Management Using Fire

Fire has been used as a land management tool for centuries in the UK (Fyfe et al., 2003) and in the last 150 years rotational burning has been used for grouse habitat management in moorland communities (Davies and Legg, 2008). Fire's role in this regard is contentious (Davies et al., 2016); however, the use of fire can serve as a genuine fuel management tool beyond its much-debated use on grouse estates and must be considered part of the toolbox in the management fire risk. Various estimates exist for the amount of land subject to some form of burning practice in the UK annually. For peatlands, Natural England (2010) suggests 1000km² (15% of deep peatlands in England) are burned annually whereas DEFRA (2010) estimated 3150km² (18% of UK peatlands). Whilst Yallop et al., (2006) suggested that 38% of Calluna dominated landscapes are managed by burning. It is unclear from these figures whether these data include all burning types (including grouse management burns). Graves and Haycock (2005) suggested as much as 16% of UK uplands were burned in areas not managed for grouse. These estimates do not contain information for lowland heathland or grasslands that are frequently managed by fire or muirburn statistics.

Santin and Doerr, (2016) defined the term prescribed fire as describing a supervised burn conducted to meet specific land management objectives. However, there are different nomenclature and practices that relate to different objectives in regard to use of fire on the landscape, which are listed following:

Swaling: Local term, largely used in the South and South West for controlled burning of moorland or heathland. This has been used for hundreds of years to encourage regeneration of vegetation. This is achieved to ensure that specific moorlands remain open and wild in character (e.g. see Exmoor National Park <https://www.exmoor-nationalpark.gov.uk/living-and-working/info-for-farmers-and-land-managers/swaling>).

Muirburn: Scottish term for the controlled burning of moorland. This aims to create a mosaic of heather patches of different ages. Providing grouse with short fresh growth and longer heather nearby in which to shelter. This also suits deer and livestock and birds, insects and reptiles, that can also benefit from appropriate, well-managed muirburn. Muirburn is guided by the Muirburn Code (2017)

Rotational burning: Largely a term used in England for burning undertaken on moorland landscapes used for Grouse habitat and shooting. It describes the planned burning of small areas of older heather in rotation over the years. The fires should be low intensity, quick, cool burns that remove the heather canopy but do not impact the underlying soil or peat. Note this practice has now been banned on deep peats (Natural England, 2021)

Controlled burning: The use of fire to remove heavy fuel loads to lower wildfire risk and/or improve land for a variety of reasons including for biodiversity or creating habitat for specific species. This term is more broad ranging in terms of usage and includes use in grasslands, heathlands, moorlands and forestry. Controlled burning makes the step towards true prescription burning. The Forestry Commission splits controlled burning into three stages: 1) Setting the objectives/prescription for the burn, 2) Planning and liaison, 3) Burning under control and extinguishing fire (Murgatroyd, 2002).

Prescribed fire: The use of fire to remove heavy fuel loads to lower wildfire risk and/or improve land for a variety of reasons including for biodiversity or creating habitat for chosen species. This approach differs from controlled burns as true prescriptions will develop use of specific fire behaviour, toward generating a chosen impact. This approach builds on controlled burns and true prescriptions of the use of fire on landscapes are in their infancy in the UK, as more research is required to develop fire usage that has well specified effects.

Tactical burn: The use of fire by FRS (Fire and Rescue Services) or land management agencies during wildfires to remove fuel ahead of the fire, to prevent fire spread in certain directions and/or to rapidly create fire breaks during major incidents. Tactical burns are controlled in their nature, for example these are often backing fire that burn against the wind preventing large flame lengths but remove fuel in controlled manner. These will not typically be designed with ecological impacts in mind beyond, preventing a large out of control wildfire spreading. These are a now a key part of toolkit that can be used in the management of significant wildfire incidents.

All of these approaches need to be fairly and separately assessed, as they are not all the same thing. Some may need to be adapted where required owing to climatic change or developed, others such as true prescriptions may in time replace traditional approaches, should the climate threat require it. What is clear is that considering fire as a blanket term and using or banning it in broad terms needs more nuance if we are to understand the implications. In the following pages are described some recent examples of the use of fire in managing fuel and habitats using controlled/prescribed burning.

Example 1 – Controlled/Prescribed burning for conservation and habitat generation: Prescribed fires have recently been undertaken in Dorset Heathland to create the correct habitat for the Purbeck Mason Wasp and to reduce specific fuels allowing the Lesser Butterfly Orchid to flourish (see Back from the Brink <https://naturebftb.co.uk/the-projects/dorsets-heathland-heart/>). Fig. E1 shows the habitat and fuel load from a Purbeck Mason Wasp burn before (2018) and after 1 year after the prescribed fire (2019), indicating the removal of a moderate fuel load of gorse and regrowth of heather following (credit C. Belcher). These types of prescribed fires are often undertaken by land managers following suitable training, the land managers in these examples were Forestry England, the National Trust and the RSPB.



*Fig. E1 Prescribed fire undertaken to enhance habitat for the Purbeck Mason Wasp
photo credit C. Belcher (U. Exeter).*

Example 2 – Removal of large fuel loads and/or generation of fuel breaks: Prescribed fires/controlled burns are being well used to remove either specific types of highly flammable fuel (such as Gorse thickets), large fuel loads and create fuel breaks to create a patchier cover of vegetation to the landscape, with the aim to prevent the spread of large out of control wildfires. The Fire and Rescue Services have gained significant capacity over recent years to undertake prescribed fires on the landscape scale. The South West FRS, North FRS, Northern Ireland FRS, Lancashire FRS and the Scottish FRS have all developed prescribed burn capabilities (Fig. E2) and the NFCC (National Fire Chiefs Council) are keen to develop and expand this skill-set in terms of managing large fire risk across the FRS sector. Likewise, landowners such as Forestry England, the National Trust, Natural England and the RSPB (Royal Society for the Protection of Birds) (as examples) have built and expanded their own capacity to manage their fuels using fire (e.g., Fig. E3) as have private landowners in Scotland via the long standing Muirburn code.



Fig. E2. Two landscape scale prescribed fires to a) remove new trees planted on a heavy fuel load of brash b) the fuel remaining after the fire load of brash and c) removal of a large fuel load of dead and downed logs d) the landscape after. Both burns undertaken by SWFRS specialist burn team, photos all courtesy of C. Hope.

Prescribed fire has a very different influence on ecosystems when compared to wildfires; prescribed fires should be designed to achieve specific goals, that are not of long-term detriment to an ecosystem. Figure E3 shows example comparisons of the effects of similar ecosystems by prescribed fire and wildfires. Fig. E3 (a, b) shows a relatively small forest plot owned by The Forestry Commission in Dorset subject to a prescribed understory fire (Feb 2020), that aimed to remove the heavy *Molinia* fuel load, the result (Fig E3b) is contrasted to the damaged caused by a spring wildfire at Wareham Forest in Dorset (May 2020) (Fig. E3c). Fig E3d and E3e show a prescribed burn to remove a heavy patch of gorse in a heathland on RSPB land on the Arne Peninsula in Dorset and the result is compared to a summer wildfire in the same fuel type at Ferndown Common (July 2018) (Fig E3f). Both of these prescribed fires were undertaken via a collaboration between The National Trust, RSPB and Forestry England under guidance by a trained wildfire consultant (WildFireTac) and with U. Exeter researchers present. Both burns were undertaken to remove patches of heavy fuels that are comprised of fire tolerant species. It can be seen that the prescribed burns did little damage to the ground in these circumstances when compared to that imposed by un-planned summer wildfires (Fig. E3b, e compared to Fig. Ec, f) in similar ecosystems.

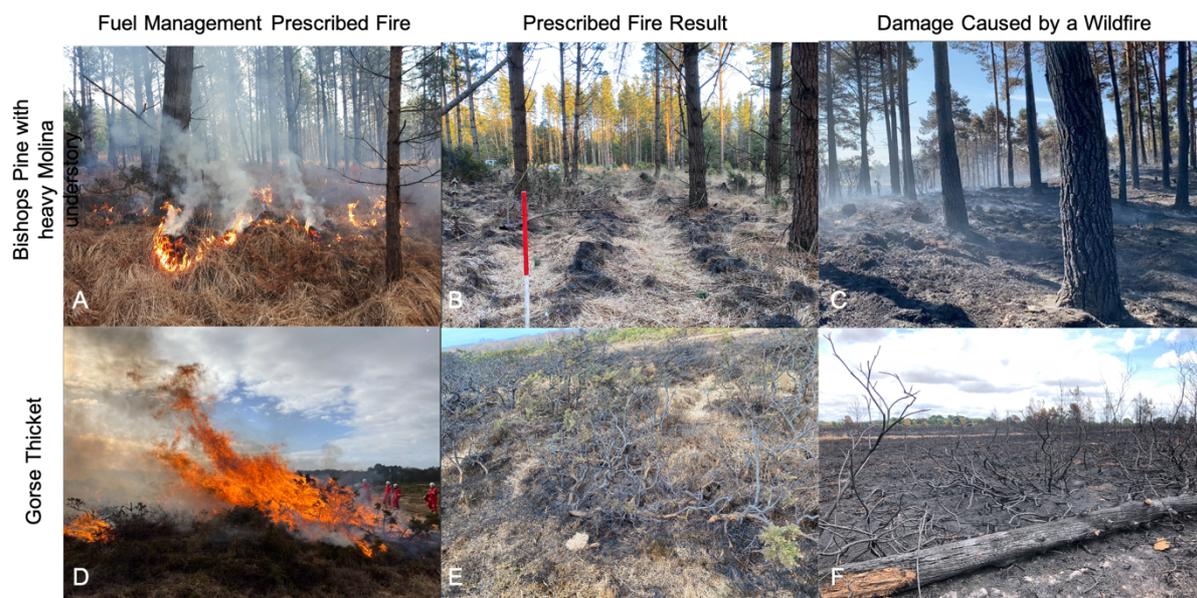


Fig.E3 Two prescribed fuel management fires undertaken by land owners and associated teams in Dorset in two fuel types compared to damage resulting from wildfires in similar fuels a) photo credit R. Gazzard (Forestry Commission) b-f) photo credit C. Belcher (U. Exeter).

Heather dominated ecosystems such as a moorlands and heathlands tend to be those that have most consistently been managed using fire as a tool. Conservation and habitat management decisions in the future may seek to replace heather dominated ecosystems in some areas with forestry or native forest (rewilding agendas) or maintain moorland landscapes as peat dominated ecosystems (Natural England, Glaves et al., 2020). Additionally, small changes may be made to increase diversity with existing moorlands and heathlands by, for example, allowing gramminoids and bryophytes to flourish in certain areas.

Currently we lack adequate information on the impacts that well-designed prescribed fires have on the UKs ecosystems and important species. There have been no long-term experiments that have undertaken properly defined fire prescriptions on specific areas and the impacts monitored, such as those of the large-scale national fire and fire surrogate studies in the USA (McIver et al., 2009). The use of fire as a management tool in some areas may have traditionally focused on a specific outcome, for example, generating new heather shoot growth for grouse feeding and patches for nesting for grouse moor management. However, in recent years there has been greater awareness of other ecosystem service benefits and disbenefits from management burns (e.g., Tucker, 2003; Glaves et al., 2013), including for wildfire mitigation, where there are significant evidence gaps for the UK context (Natural England, Glaves et al., 2020).

Concern about the environmental impact of management burns has recently led Natural England (2021) to announce that rotational burning will soon not be allowed on deep peat (>40cm) in protected areas in England. There will be specific circumstances where burning may be allowed and licences may be sought from the Secretary of State for the burning of heather on deeper peats for certain exemptions, including for wildfire prevention. Well-designed prescribed fires should have the capability to consider both species aspects and fuel management outcomes (e.g., Purbeck Mason Wasp Burns 2018). Furthermore, for all prescribed fires, a clear outcome should be that there is no significant impact on soil carbon storage, especially on peats and peaty soils. By factoring in multiple outcomes at the outset of the development of prescribed burning plans, ecosystem service trade-offs can be explicitly

considered. Therefore, research is needed in order to assess true ecosystem impacts in terms of habitat and species diversity in relation to well-designed prescribed fires. Such that we can effectively determine landscapes that prescribed fire can be beneficial too and should be used on and where this practice may be detrimental and alternatives sort. In other words, more understanding is required in order for the UK's land to be managed with the right tool in the right place. This will require cooperation between FRS, land managers, conservation, ecology and researchers in order to design specific fire prescriptions designed for multiple positive outcomes and to indicate where such fuel treatment may be inappropriate.

It should be noted that the timing of the legal burn season does not currently mimic natural fire regimes in the UK, and this is considerably debated. This causes issues in regard to limiting prescribed fire activity. The timing of prescribed fires is highly regulated in the UK under various legislation (Harper, et al., 2018). For example, prescribed fires can be undertaken between 1st October- 15th April in England, 1st October – 31st March in Wales, 1st October and 30th April in Scotland and between the 1st September and 14th April in Northern Ireland (DEFRA, 2007; Welsh Assembly Government, 2008; SEERAD, 2001). It has been argued that these dates do not allow enough fuel clearance using fire due to the high variability of weather in the UK between Autumn and Spring (Allen et al., 2016; Hope, 2017). Particularly wet winters and wet early spring can mean that many prescribed fire teams (be they land management, private or FRS led) are not able to meet their planned habitat protection and fuel management objectives which can lead to significant increases in fuel load in fire prone ecosystems (e.g. see Fig. E3 the *Molinia* in the Bishops Pine plot was not as well removed as hoped as the conditions towards the end of burn season were very wet and there was little to no wind on the day assigned to the burn). These issues could become problematic in the near future as the number of days experiencing high fire weather indices (Fig. D3 and D4) and severe fire danger will increase, meaning that a lack of ability to remove large build ups of fuel during winter months, due to short burn seasons, may become problematic. Indeed, the National Fire Chiefs Council (NFCC) have suggested (NFCC wildfire lead, pers. comm. 2020) that they would support more flexibility around this particular issue, especially if very high-risk fuel loadings were identified out of the burn season; stating that prescribed burning should be part of a toolbox of fuel management solutions throughout the year if it will prevent larger wildfires from occurring. An increase in the capacity of personnel able to undertake prescribed fires is needed and requires significant investment in effective training for both fire and rescue service (FRS) specialist teams and land managers. Investment in building competence and maintaining skills of crews is required and strong partnerships need to be generated between FRS and local landowners to enhance the benefit of managing fuel loading on the landscape using prescribed fire in order to lower large wildfire risk as we face the UK's climate challenges. The support of partnerships is essential if we are to future proof the UK's biodiversity, pyrodiversity and mitigate large wildfires.

Selection of Appropriate Fuel Management: Contrasting Mechanical versus Fire-Based Approaches

All fuel management techniques have their merits, advantages and disadvantages. Realistically, the UK's fire prone habitats were not created using any of these options in isolation and the best possible outcomes will likely only be achieved by selecting a variety of techniques. For example, traditionally, lowland heath is the product of centuries of burning, grazing and harvesting. In the case of both lowland heath and moorland landscapes the original woodlands were cleared using slash and burn and ericaceous plants, grasses and gorse grew in its place.

These areas were then harvested for fuel, thatch and animal bedding; grazed to produce meat, milk and cheese. Burning was used again to improve grazing and a cycle of grazing, harvesting and burning was established. Whilst it is not viable to return to these traditional ways, by using the best of the tools together (e.g., mechanical intervention, grazing and burning), it should be possible to conserve these valuable habitats if appropriate.

Different management practices will have different effects on the landscape, ecosystems and the environment. For example, mechanical mowing can damage some habitats by exposing the soil, hence such an approach would not be applicable where moss and litter layers actually form an aspect of wildfire protection (Grau-Andres et al., 2017). Additionally, such an approach may not be practical on steep slopes or in very wet areas (Muirburn Code 2017). For example, experiments that contrasted the effects of different fuel management approaches on shrub heathlands containing *Ulex*, *Erica* and *Calluna* in NW Spain, indicated that all treatments successfully reduce fuel height and load when monitored for 2 years compared to a control site (Marino et al., 2012). However, the different treatments showed different effects on the remaining fuel characteristics (Marino et al., 2012). The shrub height, dead fuel fraction and fuel load were higher after prescribed burning when compared to the two mechanical approaches. The two mechanical approaches trialled were shrub clearing and crushing using a tractor with a rear mounted brush shredder, that left the crushed remains on the floor; and shrub clearing and manual removal where the base of the shrubs was cut using a powered saw and the cut vegetation taken away. When tested for the flammable characteristics the shrub clearing and crushing treatment led to longer flame durations and higher flame heights than the other treatments (Marino et al., 2012). This study highlights the intricacies of fuel management practices, be they using fire or mechanical approaches, as each will achieve different effects.

It is clear that any fuel management activity, be it fire based or mechanical based, will have a feedback on subsequent wildfire effects. In terms of fire-based management, *Sphagnum* sp. (moss) may be given the chance to spread once large loads of heather are removed (Tucker, 2003) by prescribed or management fires. However, there is considerable conflicting evidence on the effects of prescribed fire on bryophyte species (Grant et al., 2012; Lee et al., 2013; Luckenbach et al., 2015) and indeed the type of bryophyte species (e.g. *Sphagnum* versus Feather Moss) has been shown to influence patterns of fire spread (Prat-Guitart et al., 2017). The presence of moss and litter in heathlands has been shown to protect the soil beneath from substantial heating during wildfires (Grau-Andres, et al., 2017). Whereas removal of moss and litter likely leads to higher post-wildfire soil temperature fluctuations and potentially increased soil respiration (Grau-Andres, et al., 2017). This is also true for the case of prescribed or management burns, where the moss and litter layers beneath heather stands have a high moisture content (>250%) and effectively insulate the soil from the fire above (Davies and Legg, 2011). Hence, well planned prescribed fires in heathlands and moorlands both have the potential do little damage to ground level fuels (e.g., see Fig. E3). Indeed, research has shown that prescribed fires aiming to manage fuel loads and rejuvenate *Calluna* should be well designed to keep fire severity low to avoid consumption of the moss and litter layers in order to minimising soil carbon losses (Grau-Andres, et al., 2017). Hence well-designed prescribed fires should be capable of removing heavy loads of heather, gorse and *Molinia* without damaging the ground understory or peat soils. Such that the impact on vegetation regeneration and soil properties, should be low (Davies et al., 2009).

Current Defra guidance suggests that burn rotations should be >15 years in UK moorlands (Defra, 2007). However, this number is much debated and varies based on local conditions and vegetation regrowth (Harper et al., 2018); both in terms of species and regrowth rate (fuel load).

Indeed, studies that include assessing the influence of rotational burning on C-emissions, which is important under the UK's 'net zero' agenda, have suggested that heather dominated ecosystems in the UK require different rotational burning from north to south. Where for northern sites the optimal rotation interval is between 30-50 years and for southern sites either between 8-10 years or 30-50 years is optimal in terms of minimising C emissions from prescribed fires (Santana et al., 2016). This implies that rather than banning of burning on heather based moorlands the average of >15 years for rotational burning suggested by Defra (2007) likely needs to be refined based on location within the UK (North to South) both in terms of C-emissions (e.g., Santana et al., 2016), fuel management for wildfire risk and for maintaining the UK's fire adapted heather communities (e.g., Whittaker and Gimingham, 1962; Davies et al., 2010; Vandvik et al., 2014).

Calluna heathlands and moorlands are semi-natural ecosystems in the UK that have resulted from human land-use since the Mesolithic (Simmons and Innes, 1987). Heathers (*Calluna* and *Erica*) are one of the dominant fuel types in the UK's fire prone ecosystems. Heather is being increasingly understood not only to be fire tolerant, but where fire has been used as part of anthropogenic management over long periods it appears to be becoming fire adapted. For example, it has been noted that heather germination can be cued by fire through temperature pulses (Whittaker and Gimingham, 1962) and that fire induced ground-surface heating from prescribed fires may promote *Calluna* seedling establishment (Davies et al., 2010). Recent research has indicated that the seeds of heather in fire managed landscapes appear to respond to smoke stimulation by fire and germinate and regrow more quickly after fire (Vandvik et al., 2014). This would suggest that where the goal is to maintain existing ecosystems such as moorland and heathland, that have been managed by fire over the historical past, we will need to develop effective burn rotations that fit within the prescribed fire season and enhance our understanding of how often to return fire to the same site for both conservation and the removal of fuel.

Prescribed burning often needs to be limited in areas where the smoke would create a hazard for major infrastructure (e.g., motorways, major roads, airports etc.) or for human health (Mitchell and Smidt, 2019). Hence mechanical fuel treatments may be well utilised in the UK's rural urban interface area, around properties and critical infrastructure (Glitzenstein et al. 2006). Additionally, fuel reduction practices at the rural urban interface will be influenced by public acceptance of the technique chosen. In this arena prescribed fire does generate some controversy in regard to air quality concerns by local residents and the threat of fire escape (Winter and Fried, 2000). However, as with prescribed fire, land managers will need to choose the type of equipment and operational parameters carefully, such that even mechanical fuel management needs to prescribe desired outcomes. This will include decisions on the resulting size particles that will be produced (Mitchell and Smidt, 2019) and how or whether they will be removed from the treated site as these will influence wildfire risk even after treatment (Marino et al., 2012). Nonetheless, there remains a lack of knowledge about the ignition and spread potential of fuels submitted to mechanical fuel reduction treatments, especially shrub clearing (Marino et al., 2010).

All treatments have economic and ecological constraints. For example, it may be costlier to apply mechanical treatment in large areas, even though the products from mechanical fuel removal approaches may have marketable value. A careful cost-benefit analysis is important when determining an appropriate fuel treatment strategy. Therefore, wildfire mitigation and management are a social-economic and socio-ecological challenge, both of which need to be considered together. The challenge is to determine what and how much landscape needs to be

treated to mitigate large wildfire risk (e.g., where are fuel load increases the greatest) and to choose what and where strategic fuel treatments will be best placed (Agee and Skinner 2005). It should be noted that the cost of not undertaking appropriate fuel treatments, is that the UK will see larger and more damaging fires in the future. Here Fire and Rescue Service (FRS) incident commanders and fire chiefs will not put their firefighters in danger to bring high fuel load intense fires under control. Highlighting that fuel management versus incident response capability are strongly interlinked. To conclude, there is no single solution to managing fuel but that the desired effects of the treatment need to be assessed holistically with a view to both wildfire mitigation and habitat management. What is clear is that more research is required to understand 1) the response of key UK species to prescribed fire, be they current dominants or those that might be used to adapt our landscapes, 2) the impact and effectiveness of mechanical treatments on wildfire risk and soil carbon.

Managing Fuel during Wildfires

Wildfires can be fought by direct and indirect tactics. Direct attack is where firefighting personnel work at or close to the fireline attacking the flames directly. During indirect attack the suppression activities are away from the fireline. This can include tasks such as creating fire breaks and fuel breaks that provide control lines where the once the fire reaches them it will become easier to action. Wildfire suppression is limited by a combination of the current fuel state, topography and weather. Climate change will make this more challenging for FRS and land managers. The only part of this that can be managed is the fuel, so it is essential that we look to fuel management as a wildfire adaptation process. Currently the UK FRS is only able to fight wildfires using direct techniques for fires of low to moderate intensity i.e. fires with flame lengths less than 3.5m. The UK is likely to see many more wildfires with high to extreme fire intensity in the near future which will require adaptation of suppression techniques, including a much wider adoption of indirect methods. Without significant FRS re-training, continual professional development and investment in new equipment, this will inevitably rely on land manager intervention and assistance (Fernandes, 2013).

The use of mechanical and manual means in wildfire response is well established in both the United Kingdom and internationally. The majority of large wildfires or Major Incidents use indirect tactics using heavy and medium plant machinery such as bulldozers, excavators and mulchers, as well as hand tools including chainsaws to create new firebreaks and fuel breaks, or improve existing features (roads, tracks etc.) to provide control lines (Oxborough and Gazzard, 2011). The use of other hand tools, such as clearing saws, backpack blowers and others, is well established for either prevention work or to establish control lines for prescribed fire as well as during incidents. Whilst there is good understanding of the use of mechanical and manual means by FRS, the vast majority of implementation is undertaken by land managers and foresters due to health and safety competency requirements. Additionally, land managers also have a better understanding of site hazards, resilience features and landform to ensure response operations are undertaken effectively, building on prevention measures established before the incident protecting key infrastructure and habitats (Oxborough and Gazzard, 2011).

Fire itself can be used in firefighting and this is known as tactical burning. Tactical burns can either: 1) be used as a defence where a controlled fire is lit with the aim to remove fuel ahead of the approaching fireline so that the fire runs out of fuel to burn or 2) controlled burns can be used to burn towards the fireline (usually as a backing fire), this not only removes fuel but the

flames are pulled towards one another bringing the fire to a conclusion in a chosen area. At least five UK FRS now routinely make use of tactical burning as a tool for both prevention and intervention of wildfires (NFCC wildfire prevention manual 2018). For example, South Wales FRS now use controlled fire as part of their wildfire toolbox to both manage fuel in terms of fire prevention as well as using fire in tactical burns to contain large wildfires. Hence, there is a growing movement within the UK to implement the use of controlled tactical burning actively during a wildfire (NFCC wildfire prevention manual 2018). Tactical burns have recently been used in several major UK wildfire incidents (e.g. Wareham Forest, 2020), and have been used on huge scales by many other nations for decades (e.g. USA). Such approaches can be very effective as they can reduce the overall resources required (NFCC wildfire prevention manual 2018) at large fires and allow FRS and land managers to focus on mitigating the effect of large fires on key infrastructure within or close to the burn perimeter. To conclude tactical burning can be used effectively as part of an operational response where it can provide, among others, the following benefits:

- Reduction in the time taken to extinguish a wildfire and mitigate its severity
- Reduction in the overall number of personnel and appliances required at an incident, reducing response costs.
- Improved firefighter and public safety.

There have been some excellent examples of the use of tactical burns in recent major UK wildfires, as shown in Fig. E4 below.



Fig E4. examples of tactical burns used in the UK recently. A and b are of tactical burns used at the Wareham Forest incident (see case study) and c and d in the Brecon Beacons to stop a large wildfire spreading across the national park.

Natural Environment and Assets: Linking Socio-Economic and Policy Aspects to Future Wildfire Activity

One key way in which fire activity is influenced by socio-economic factors and policy drivers is through changes to land use via legislation or economic incentives. Changes to land use have the potential to alter the type, amount and connectivity of above-ground fuels, with consequent knock-on impacts to wildfire risk. Many current national and local environmental policies centre around the Net Zero agenda (Committee on Climate Change, 2020) as well as the transition in Agri-environment policies following Brexit. These represent potentially significant and long-term changes in the way that many parts of the UK landscape are managed. In addition, emerging agendas such as rewilding (e.g., Rewilding Britain) have captured public, academic and policy attention requiring us to consider the role of what we want our landscapes to look like in the long-term. The 25 Year Environment Plan (HM Government, 2018) provides a platform to bring together many of these interconnected issues. Individual policy drivers may promote certain land uses over others and over different spatial and temporal scales. In practice, however, these drivers do not exist in isolation and must be viewed holistically.

Policy and Risk Assessments

Wildfire as a natural hazard defined by the Cabinet Office (Keeping the Country Running, 2011) cuts across various legislation but is not named or referenced specifically. We note that the following legislation, its dependent programmes and planning are relevant to wildfire in terms of adaption to climate change:

- Climate Change Act (2008)
 - Climate Change Risk Assessment (2012 and 2017)
 - National Adaptation Programme (2013 and 2018)
 - Adaptation Reporting Power
- Civil Contingency Act (2004)
 - National Risk Assessment/Register and future National Security and Risk Assessment
 - National Resilience Capabilities
 - Community Risk Assessment
- Fire and Rescue Services Act (2004)
 - National Framework

Whilst wildfire has been considered in many of these legislative actions, it has been suggested that the lack of a coherent multi-stakeholder consultation, approach and strategy continues to make climate linked wildfire mitigation and adaptation challenging. For the UK to develop and implement adaptation to wildfire then the key acts of the parliaments must work together in a synergistic manner, despite them not being specifically designed to do so. Additional legislation and regulation for wildfire prevention and response, for key landowners in fire prone landscapes, is now critical as well as the development of central resources to enable interagency working before, during and after incidents. Such legislation needs to be designed over longer durations than typical short-term policy structures, that tend to act over non decadal planning. The nature of climate-change and the associated increase in fire threat (e.g., Fig. D4) will occur from yearly to decadal timescales hence long-term planning is required beyond that of typical short-term policy and legislative if we are to provide effect forward planning. If action is not undertaken soon and further opportunities are missed across departmental plans, policy and incentives, the cumulative weaknesses could significantly increase future prevention and

response costs, restrict or damage natural resilience assets, as well as result in a considerable increase in impact to the environment, property and people.

Brexit and Agricultural Policy

Following the UK exit from the European Union, new agricultural policy will be rolled out to replace elements of the Common Agricultural Policy (CAP). Over the coming years, the Basic Payment Scheme will be phased out and instead be replaced by a system of “public money for public goods” (UK Government, 2020) whereby land managers deliver public goods (e.g., clean water, biodiversity, climate change mitigation) alongside market goods. The Environmental Land Management (ELM) scheme is the key delivery mechanism. Any long-term changes to land use could have important impacts on how fuels accumulate and consequent impacts for wildfire. Scenario development for future land use is a key approach to exploring complex trade-offs (e.g., Reed et al., 2009), however, we have found none that consider the impacts on wildfire or other environmental hazards in the UK. Wildfire must be considered alongside changes in agricultural policy owing to the enhancement of wildfire risk.

Rewilding Agendas

A growing area of public, academic and policy interest (e.g., Alison and Wentworth, 2016, Carver, 2017) is that of rewilding. Rewilding can be thought of reinstating natural processes to address the continuum of human modification of landscapes over recent decades and centuries (Carver, 2017). These could range from reintroductions of iconic species across large areas (e.g. wolves in Yellowstone National Park, USA) through to small scale interventions such as leaving parts of parks and private gardens over to nature (e.g. ‘no mow May’). Rewilding is considered to have its greatest power in counteracting greenhouse gas emissions where large areas of degraded landscape are returned to a healthy state to improve carbon capture (Strassburg et al., 2020). Rewilding will not be appropriate or desired everywhere, but where it does take place, and where fuel loads could change (amount and type), there needs to be recognition that wildfire risk should be considered. Additionally, the term re-wilding needs clear definition as currently this term appears to be used for a range of possible land use and land management possibilities from ecosystem restoration, trophic rewilding through to leaving small areas of people’s gardens to nature. These will have significantly different greenhouse gas mitigation potential and implications for wildfire risk.

Greenhouse Gas Removal Through Enhancing Carbon Sinks

As noted elsewhere in this report, climate change will have significant impacts for wildfires, such as increases in ignitions (e.g., lightning, Mariani et al. 2018), more conducive fire weather days, or a longer fire season. Tackling anthropogenic climate change requires a significant step-change in how we regulate greenhouse gas (GHG) emissions, as well as how we manage our existing carbon sinks (e.g. forestry, peatlands). However, the effect of reductions in GHGs is likely to take a long time to realise changes to the climate system and consequently wildfire activity remains likely to rise even if GHG targets are met. In the immediate to medium term, careful management and enhancement of existing carbon sinks may be one way in which the effects of climate change can be mitigated. The target set by the UK Government in 2019 to achieve ‘net zero’ by 2050 (UK Government 2019a) requires reductions of 15.5 MtCO_{2e} per

year over the next 30 years (Committee on Climate Change, 2020). As part of the range of options available to meet these targets, changes to land use across the UK have been proposed to facilitate greenhouse gas removal from the atmosphere, which include increases in tree planting, restoration of peatland, and encouragement of bioenergy crops (Committee on Climate Change, 2020). Changes to land use could have the potential to change the fuel loading, such as increases in above-ground fuel following afforestation, or shifts in species assemblages following rewetting of peatlands. In any scenario, fire risk should be considered and be reviewed throughout any transition. Whilst there will be short-term changes following land use change, the target vegetation community may take many years or decades to establish. For example, following peatland restoration on degraded sites in the Peak District National Park, Alderson et al. (2019) showed that whilst immediate changes to vegetation cover occurred rapidly (<1 year), it took over a decade for key indicator species to re-establish. Therefore, an understanding of changing fire risk throughout ecological succession and of the final ecological community must be considered in such schemes.

In addition to the carbon benefits brought about by careful land use, there are a range of other ecosystem services that may benefit from changes in how our landscapes are managed (e.g. flood mitigation, improved biodiversity). The multi-benefit approach to land management is embedded throughout the 25 Year Environment Plan launched in 2018 (HM Government, 2018). Nature-based solutions are increasingly being used to tackle socio-environmental challenges, so it is by working with natural processes that it may be possible to better protect from environmental hazards such as wildfire.

Infrastructure: Civil Contingency

Wildfire Incident Response and Capacity

Currently the Fire and Rescue Services (FRS) across the UK have the responsibility to respond to wildfires and determine the means of suppression. They have different legislative and administrative arrangements for England, Wales, Scotland and Northern Ireland. (Fire and Rescue Services Act 2004 – England and Wales, Fire and Rescue Services Order 2006 - Northern Ireland and the Fire Act 2005 - Scotland). This means that there is no single point of governance, legislation or training standards across the different administrations. The National Fire Chiefs Council (NFCC) spans all FRS administrations. However, the NFCC is an advisory body only with no statutory responsibilities. It currently (2021) administers the National Wildfire Tactical Advisor cohort. This is an exclusively FRS resource and consideration could be given as to how other sectors can be included in this national capability.

Each Fire and Rescue Service determines its response priorities based on a risk assessment; in England this is the Integrated Risk Management Plan (IRMP). This IRMP should set out the Fire and Rescue Authorities strategy in regard to fire but also wildfire capturing how these will be considered in collaboration with other agencies in reducing the commercial, economic and social impact of wildfires (Communities and Local Government IRPM policy guidance document 2008). This then determines the allocation of resources, the equipment and training etc. required by each individual FRS. The primary fire risk in the UK is considered to be from structural fires and consequentially, the majority of FRS are equipped and trained to respond to structural fires but not wildfires.

A survey was undertaken in 2015 by a group comprising representatives from academia, the NFCC and the Forestry Commission as to the extent to which wildfire was included in Fire and Rescue Services (FRS) IRMPs across the UK (McMorrow, Hedley, Gazzard 2015). This indicated that ~60% of FRS had considered wildfire in the IRMPs, around 50% had included wildfire in their IRMPs and ~55% had wildfire included in their area and local service plans (McMorrow, Hedley, Gazzard 2015). 70% of FRS did describe wildfire as a specific risk on their Community Risk Register. Regional variations were found in regard to the inclusion of wildfire in FRS IRMPs with the eastern UK counties lacking reference to wildfire (McMorrow, Hedley, Gazzard 2015). A more recent study that focussed on wildfire adaptation and contingency planning in South East England (Moffat and Gazzard, 2019), indicated that of the 8 Fire Authorities assessed, 2 out of the 8 made no reference to wildfire, of those that did include wildfire it was not seen as a priority and 2 (Buckinghamshire and Surrey) mentioned the link between climate change and wildfire. When the occurrence of wildfires per region was compared with the occurrence of wildfire risk mentioned in IRMPs there was little correlation. Where even in regions that had a considerable number of wildfires (>1ha) they may or may not have included wildfire in their IRMP (McMorrow, Hedley, Gazzard 2015). Hence the lack of consideration of wildfire as a risk in FRS IRMPs is not a reflection of a lack of wildfires in a region but rather suggests a lack of recognition of the risk. These analyses suggest that only ~50% of FRS in the UK have an awareness of wildfire as a risk in their region and likely much fewer have an awareness in terms of forward planning for climate-driven increases in wildfire threat (e.g. Moffat and Gazzard, 2019).

These analyses are supported by a separate report (NFCC wildfire prevention manual 2018) that suggests only a small percentage of FRS, around 10% (5 out of 52), have made special provision for wildfire or climate change induced wildfire specifically. This current predicament limits the UK's potential to mitigate the increased occurrence of large wildfires and adapt in the face of climate shifted fire regimes. The Communities and Local Government Policy review (2008) suggest that IRMPs are best planned and implemented at a local level so that they are based on local needs but notes that there should be consistency in approach and quality in regard to IRMP production. We suggest that the inclusion and consideration of wildfire risk should be made mandatory for all Fire and Rescue Authorities (e.g., Arnell et al., 2021). This would not only allow assessment of genuine wildfire risk but would also allow all Fire and Rescue Authorities to enhance their preparedness to assist with large wildfires outside of their region, as is often required in large events (e.g., Saddleworth Moor 2018). Moreover, the National Framework 2008-2011 requires each Fire and Rescue Authority to produce an IRMP covering a minimum of a 3-year time span. As with many other risk-management planning and policy making decisions this is too short a time period to capture the long-term planning required to adapt to the predicted changing fire regimes over the coming decades.

Because of the critical role of IRMPs in determining allocation of resources for FRS, for those authorities that have not included wildfire in their IRMPs this implies that at least half of the UK's FRS will not have been provided with wildfire specific Personal Protective Equipment (PPE), or specialised wildfire training at this point in time. The lack of full accredited wildfire training for many crews also limits the response capacity of the UK to assist other nations in facing extreme wildfire seasons, such as those seen in Australia in late 2019 early 2020, where firefighters from several nations went to the aid of Australia during this crisis. Accredited wildfire training is available to both FRS and land managers in the UK (Lantra 2002 – accredited training scheme). This 1-day long training course is classroom based and primary focussed on indicating how farmers, estate workers and land managers can work effectively with FRS and other authorities to suppress wildfires in a timely and safe manner. This course

covers the basic theory of wildfire behaviour, suppression techniques and health and safety. However, it does not provide practical wildfire suppression and fuel management training, which is essential in preparing FRS and land managers in the UK for future fire threats. Our FRS and land managers will require training in the management of high and extreme fire intensity as we move forward, including in indirect attack approaches (which are required when flame lengths are greater than 2.5m), such as aerial attack and tactical burning.

Regarding firefighting infrastructure and additional expertise, the Communities and Local Government IRMP policy guidance document (2008) states that ‘In aiming to successfully deliver wildfire strategies, the FRS will need to work in partnership with other stakeholders.’ As such each FRS needs to identify the most appropriate stakeholders and generate working relationships effectively together to deliver the shared goals of a wildfire strategy. Stakeholders and policy advisors, such as Natural England, the Forestry Commission and the Environment Agency, National Parks as well as Local Authority Officers are good examples. Clearly the FRS will have the operational lead on suppression, but land managers and conservation bodies all play an important part during major wildfire incidents.

Wareham Forest, May 2020 in Dorset is an example of a large wildfire that incorporated many different agencies. The Dorset and Wiltshire Fire and Rescue Service were the lead FRS for suppression. A Major Incident was declared and lasted for several weeks. Assistance was required from several other FRS including National Wildfire Tactical Advisors and a Tactical Burn Team. A National Police helicopter provided some aerial support as did both FRS and Police drone teams. But in addition to the blue light resources, a helicopter was deployed by Forestry England, a Bulldozer was provided by an adjoining land manager, several other land management agencies (The National Trust, RSPB, Natural England and Local Authorities) provided mowers, mulchers, bowsers, chainsaw crews and fire fogging equipment. Personnel were also provided by Forestry England and The Forestry Commission to provide land management advice in respect to wildfires and conservation. Conservation groups were involved in rescuing wildlife, predominantly reptiles and a team of wildfire researchers attended to gather essential data.

The Chobham Common wildfire in Surrey, Aug 2020 was also declared a Major Incident. It also required several FRS to attend including National Wildfire Tactical Advisors. A National Police helicopter provided aerial support and the local Mountain Rescue Team provided logistical support in the form of an incident command unit and drone capability. Two ambulance service trusts attended along with Railway Incident Officers, Police, Electricity and Gas board officials, bulldozer and excavator operators, tractor mounted mowers and two local councils.

Both of the brief case studies outlined above managed to bring the incidents to a successful conclusion, but both struggled to manage the complexity of a landscape scale incident requiring many different agencies to attend. There are a number of ad-hoc arrangements in place to encourage close working between FRS and other agencies such as the Wildfire Forums and the Fire Operations Groups (FOGs). However, there are no nationally agreed protocols to enable joint working and this may add to the uncertainty around the risk. In other parts of the world there are many good examples of integrated response to wildfires. This integrated approach includes prevention, protection, response and recovery. A national integrated management system could have enhanced the performance at both Chobham Common and Wareham Forest. The National Coordination and Advisory Framework (NCAF) could be seen as a high-level

starting point for managing large scale major incidents, but it currently lacks the local implementation of an integrated management system.

Infrastructure: Health, Services and the Built Environment

Water Supplies

The large Saddleworth/Stalybridge Moor fire in Greater Manchester in 2018 affected an area that contained several large reservoirs that form a major part of the water supply for the region. During the fire the landowners United Utilities drained reservoirs in fire effected areas before significant contamination could occur (from ash, organics and heavy metals), saving the water and adding it to other reservoirs. United Utilities estimated the cost of the wildfire to them to be in the region of £700,000 which included them funding helicopters for firefighting, resources to support the emergency services and immediate repairs to the catchment land. In terms of habitat restoration, they estimate the costs following the wildfires to be on average ~£1500 per hectare. A team of researchers from Swansea University worked with United Utilities to look at risk assessments for their unburned catchments and they found that by applying the recommendations of the research there would be a cost avoidance against of up to £1 million for each future wildfire avoided. This highlights the importance of collaborations and the benefits of building tailored risk assessments around wildfire mitigation to landscapes that provide major services.

Road Networks and Transport

Wildfires can cause road closures either owing to the road being within the boundaries of the fire itself e.g., Sugar Hill, Wareham Forest, 2020; The A3095 in the Swinley Forest, Crowthorne Wood, 2011, or due to the issues of smoke travelling across roads. This causes local access issues, rerouting of traffic and traffic delays, particularly on major roads. The closure of the A3095 during the Swinley Forest fire had a significant impact. The road was closed for a week and traffic rediverted. 25,133 vehicles per day are estimated to have been diverted (Aylen et al., 2015). This added an extra 2 miles per day to vehicles journeys, the cost for this closure, delays and rerouting has been estimated to have cost £229,292 (or £32,756 per day). Such costs would be considerably greater where large wildfires might interact with major motorway infrastructure; as an example, 69 billion vehicle miles were travelled on Great Britain's motorways in 2018 (UK Government, 2019b), with motorways such as the M25 carrying 169 thousand vehicles a day and the M6 and M60 >45,000 per day (UK Government, 2019b). These three motorways are some of the busiest in the UK and also pass through fire prone landscapes. The M25, passing the Surrey Hills, the M6 through several upland moorlands and the M60 through the moorlands of the peak district. The majority of the UKs motorways are distributed in the regions of the UK that will likely see the greatest percent increase in the number of high fire dangers in the future (Fig. E5).

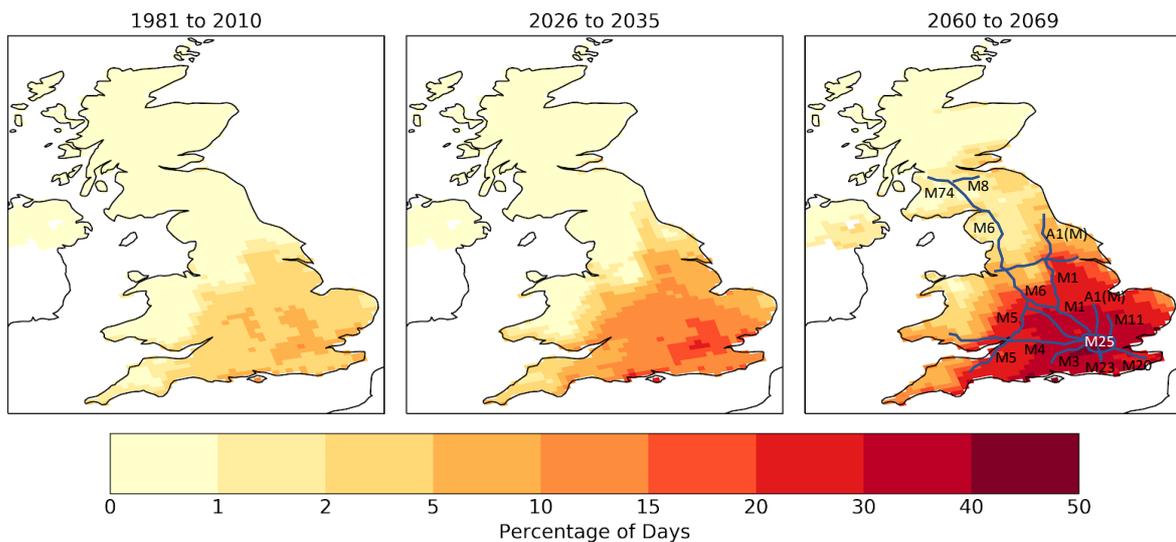


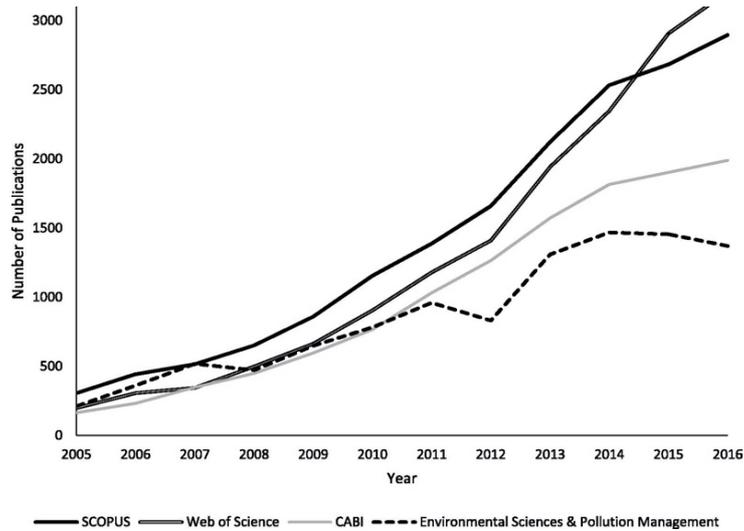
Figure E5: Annual occurrence (% of days) with Fire Weather Index (FWI) > 17.35 (Fire Danger Class 4/5) during summer (JJA) from the UKCP18 12km regional model averaged over the 12 ensemble members for a) 1981-2010 baseline period b) 2026-2035 (2 degC global warming level) and c) 2060-2069 (4 degC global warming level), with UK's motorway network indicated.

Health and Wellbeing Agenda

As part of both environmental and health agendas, there has been a push by successive governments, as well as charities and third sector organisations to encourage greater engagement with the natural world and green spaces as this has clear benefits for health and wellbeing (e.g., White et al., 2019). Through increased access and visits to green spaces, particularly in the urban and peri-urban environments, there is the potential for increased occurrences of ignitions. Locations such as popular tourist car parks and national trails and footpaths in the rural landscape, as well as the more nebulous rural-urban interface, are key areas where wildfires are known to start (e.g., Wareham Forest) (McMorrow and Lindley, 2006, Dixon and Chandler, 2019). Individual FRS or land owners and managers are likely to be familiar with these areas and will target interventions accordingly. These will include preventative measures (e.g., public information campaigns at times of high fire risk), as well as increased monitoring of human activities in at risk areas during the fire season.

Recognition of Ecosystem Services and Natural Capital Assets

Assessments of ecosystem services have become a valuable tool for assessing and managing relationships between ecosystems and human activities (Busch et al., 2012; McDonough et al., 2017). Fig. E5 shows the significant increase in the number of publications considering ecosystem services over the past 10 years.



*Fig. E6 number of publications mentioning ecosystem services over the past 10 years.
Figure taken from McDonough et al., 2017.*

Despite the recognition that ecosystems provide services to our culture in a myriad of ways, the National Risk Register does not value Natural Capital Assets, which are currently worth approximately £761 billion (ONS, 2018). Such Natural Capital Assets and ecosystem services are heavily affected by wildfires, via changes to public health, carbon sequestration and by generating emissions (Gazzard et. al. 2016 and Wentworth and Shotter, 2019). Estimates of key assets and services include £588 million from water extraction, £227M from timber and £2.4Bn from agricultural biomass, while natural regulating services underpin £1.5Bn of carbon sequestration (especially in deep peats and timber), all of which are vulnerable to wildfires. As an example, United Utilities had to drain and abandon an entire reservoir owing to the Saddleworth Moor fire, which threatened several reservoirs with pollution. As such adaptation steps should be considered by the government in regard to the UK’s ecosystem services and natural capital assets as these are currently not recognised as an environmental capability.

Moreover, the refocusing of approaches to link with ideas of natural capital embedded within the 25 Year Environment Plan (Curnow, 2019) could also see a change in how wildfires are ‘accounted’ for. For example, can we ‘value’ the carbon lost during recent wildfires or the increased hospital admissions associated with a large-scale smoke event (e.g., Saddleworth 2018; Graham et al. 2020) and weigh this against those preventative options for managing the risk ahead of time?

Challenges for Wildfire Adaptation in the Built Environment and at the Rural / Urban Interface

Where the natural environment adjoins the built environment or significant infrastructure is known as the Rural-Urban Interface (RUI) in the UK. This is akin to the Wildland Urban Interface (WUI) of other nations, but because the UK has very few true wildlands it is described as rural. In either case the challenge lies with the intermixing of high-risk wildland/semi-natural fuels and the built environment which increases the risk of ignition but also disruption, damage to and/or destruction of property and of course threatening lives (Gazzard et al., 2016).

Building codes for fire safe design have been used for structural fire protection for decades in many other countries. For example, The National Fire Protection Agency (NFPA) in the US has building codes for both structural and wildland fire threats and more recently New Zealand land use planning and capacity has been introduced in RUI situations (Kornakova and Glavovic, 2018). Such building codes include guidance for the appropriate layout, building materials as well as emergency access and escape routes planning designed to standards and codes (e.g., Deaton, 2017).

To date RUI wildfire risk has not been considered in UK building regulations and in general building fire safety regulations in the UK only anticipate ignition from the inside and not from that such as ember ingress from wildfires. Whilst, UK housing might appear fire resistant in respect to wildfires it should be noted that hundreds of the homes were destroyed by a wildfire that hit Mati in Greece, 2018 and 102 people were left dead. The homes in Mati were all traditionally built of concrete and brick construction with tiled roofs, similar to that common in the UK and the nature of the planning of the housing layout made egress from the area highly difficult. The disaster in Mati serves as a good case study for which to consider the worst-case scenario for a UK housing estate or small town within the UK RUI in fire prone regions. This, and an increase in the popularity of timber frame construction for a range of building types highlights that wildfire and sources of ignition from the outside of buildings should be considered in future planning actions and in review of building regulations and standard codes. Incorporating wildfire adaptations in to building and planning policies is becoming common place in many nations including the US, New Zealand and Australia (Gazzard et al., 2016; Pearce et al., 2019). Such building and infrastructure adaptations to wildfire should be thoroughly reviewed and mitigative measures put into action in regions that are suggested to become the most fire prone within the UK in the years to come.

It should be noted that some proactive UK communities living in high wildfire risk areas have engaged with the UK's arm of the NFPAs Firewise scheme which provides guidance to property owners on how to make their home and gardens less at risk from wildfires. This initiative has been taken up by three UK communities so far. But does show that residents at the RUI and close to areas of natural beauty are engaged in mitigating risk in fire prone regions. This scheme has been supported by the FRS who work together with the residents in the scheme.

F) Executive Summary of Evidence and Recommendations

Summary of Evidence

In recent years several large-scale UK wildfire events have led to heightened interest in building an understanding in their behaviour and impacts. 2019 eclipsed the record for the largest burnt area (29,152 ha) and highest number of fires (134); records that were previously held by 2018. Whilst, not reaching the activity the of 2019, the 2020s saw as many fires as 2018 but slightly less overall burned area. In general, large, burned areas occur on average every 5 years in the UK. Future projections of fire risk in the UK have recently been analysed using the UKCP18 climate model. These project that under a 4°C warming scenario the % of summer days experiencing very high fire weather index may be as many as 55%. Under a 2°C warming scenario 27% of summer days might experience very high fire weather index. These compare to a mean of 9.3% of summer days between 1981 and 2010 (as the baseline). Alongside increases in fire weather indices, it seems likely that climate and CO₂ driven changes to vegetation type and growth will occur. Some regions will naturally gain vegetation whilst, some may lose it and some may experience a gain in woody biomass. This is anticipated to increase the UK’s fire proneness and enhance the fraction of land burned. This key evidence is summarised in Table 1.

Evidence Category	Description	Current Trend or Observation	Predictions for Change
A1	Wildfire Seasonality – Spring Fires	Most wildfires in the UK occur in spring (March, April and May). Typically, the Spring has the largest area of land burned by wildfires which is due to a lot of small fires (Figs. C3b and C4)	<p><i>UK Average Predictions</i></p> <p>The UKCP18 models suggest a slight increase in UK averaged dangerous Fire Weather Indices during the spring between now and 2080. This varies for the different global warming scenarios, with a predicted increase in the % spring days with very high fire risk being as high as 9% for a 2°C warming, and as high as 15% under 4°C (compared to reference of 2% for 1981-2010) by 2069.</p> <p>However, recent reanalysis by the UK Met Office suggests that these are underestimates (Fig. D1a), as it seems that the models appear to underpredict high FWIs in the Spring.</p> <p><i>UK Spatial Variations</i></p> <p>There is little change overall in terms of the areas affected by wildfires but rather increases in the % of days of high fire weather indices. High fire weather indices occur most frequently over central and southern England and the coastal areas of northern England, Scotland and Wales. Into the future these areas will see a slight rise in the % of days experiencing very high FWIs (Fig. D3).</p>

A2	Wildfire Seasonality - Summer Fires	The summer months of June, July and August also have a significant number of wildfires. Whilst summer has fewer overall fires than spring, currently summer fires tend to attain larger burned areas. (Figs. C3b and C4)	<p><i>UK Average Predictions</i></p> <p>The UKCP10 models show a dramatically increasing trend in the number of summer days (averaged for the UK) with very high fire weather indices. This varies for the different global warming scenarios, with a predicted increase in the % spring days with very high fire risk being as high as 27% for a 2°C warming, and as high as 55% under 4°C (compared to reference of 2% for 1981-2010) by 2069.</p> <p>Recent reanalyses by the UK Met Office suggests that these trends appear well predicted (Fig. D1b).</p> <p><i>UK Spatial Variations</i></p> <p>There is little change overall in terms of the areas affected by wildfires but rather increases in the % of days of high fire weather indices. Very high FWIs are predicted to be concentrated in central and southern England but these areas are predicted to expand and intensify, e.g. large areas are likely to exceed having 30% of summer days as experiencing very high fire weather (Fig. D4).</p>
B1	Periodicity in UK wildfires	Over the last 20 years, annual totals for burned area seem to suggest that large burned areas occur approximately every 5 years in the UK. (Figs. C3a and C7).	There are no estimates that consider changing periodicity in wildfires for the UK. So, we anticipate that this pattern will continue, but, based on the increase in the % of days that will experience high FWIs in the future, burned areas in all years will be enhanced and that if the apparent periodicity in wildfire continues that burned area will likely increase in the future.
C1	Recent trends	The fire seasons of the last 3 years have seen the largest burnt area and the largest number of fires (Fig. C8). This trend also appears to be the case for other northern European countries (Fig. C9)	Some studies have shown a progressive increase in the probability of wildfires across the whole of the UK throughout the 21 st Century (Fig. D6) and in annual burned fraction for some regions of the UK (Fig. D7). The predicted increase in annual burned fraction appears to relate to increases in fuel loads in some regions (Fig. D8) and in some cases a shift in the dominant fuel type (Fig D9).
D1	Wildfires according to land cover class and changes in land cover class and fuel load	<p>The largest number of UK wildfires occurs in grassland habitats. Whilst the largest burned areas occur in Heath (lowland heath) and Bogland (peat-based moorlands) (Fig. C6)</p> <p>Some studies have suggested that some parts of the UK (Scotland) will become more woody (deciduous woodland) and less grass dominated in</p>	Around 65% of England and Wales lowland Heathland habitat occurs in the regions predicted to experience >20% of summer days of very high fire weather indices by 2069 (Fig D4). This compares to just 5% of days experiencing very high FWIs between 1981 and 2010. Hence, large burned areas will be highly likely in this habitat type in the future. Likewise, moorland areas will see an increase in the % of summer days experiencing very high FWIs (as high as 10% of summer days). Grasslands occur across large areas of the UK, therefore

		<p>the future, largely due to increases in CO₂ (Fig. D9).</p> <p>Some regions have been suggested to see a decrease in fuel load (~10% in Scotland) whilst others are anticipated to see an approximate 30% increase in fuel load (particularly Wales, North York's Moors, Peak District, South Downs and Higher Weald) (Figs. D8 and D9).</p>	<p>increased fire frequency would also be anticipated in this habitat.</p> <p>The combination of CO₂ driven changes in fuel coupled to climate driven changes in fire will lead to increases in burned fraction in the next 60 years, particularly in some of the UKs existing fire prone landscapes (Fig. D7-9)</p>
E1	Wildfire Climate Feedbacks	<p>The majority of wildfires in the UK likely make no net contribution to atmospheric carbon dioxide levels as the vegetation regrowth balances that which has been emitted. However, moorland wildfires which often account for the largest burned area in the UK can be net contributors to atmospheric CO₂ when the fire transfers from the surface fuels into the peat, this organic soil can smoulder for many weeks and is particularly difficult to extinguish. This can release long-term stores of C. This does not occur very frequently at present but may become more of an issue in the future.</p> <p>In the Saddleworth Moor fire that burned some 18km² of upland, in the severely affected areas, the average depth of peat loss was 6cm (see Fig. B8). This represents a considerable loss of legacy carbon. The fire is estimated to have emitted 36,720 t of carbon; the majority being long-term losses from peat soils.</p>	<p>Drier conditions associated with projected increase in air temperature and evapotranspiration have the potential to enhance the ignition potential of peatland surface fuels in the future. Peat re-wetting schemes will have to make sure that a high water table remains in the summer months, and whilst high water tables are not suggested to prevent ignition and spread in surface fuels, this may prevent transfer to fire to the peat soil.</p> <p>Projected changes in vegetation species composition, be it through climate-driven changes in fuel loads and type (e.g. Fig.D9) or due to modifications in peat moisture content, are expected to directly influence wildfire risk and severity in peatland ecosystems.</p>

Impacts and Adaptation Recommendations

Our ability to adapt to the likely changes in UK fire threat and fire regime are dependent on the actions that we set for the decades to come. We will need to assess what changes we might expect in our ecosystems in terms of vegetation changes because vegetation is the fuel for fire. It is clear that more UK specific research is required to predict climate and CO₂ driven shifts in vegetations types and distributions. Once this knowledge is in hand land managers will need to determine what habitats should be allowed to shift with climate and what others might be maintained as existing designated habitats. In either case fire risk must be considered in all circumstances in fire prone regions and ecosystems both for habitats that will be maintained and during transitions to or additions of other vegetation types. How shifting fuel types and loads will be managed needs to be considered in terms ecosystem impact, practicality and economic cost as well as in considering the impacts that management plans will have on the carbon cycle, especially carbon sequestration. Future land management approaches will include managing fuel using fire, mechanical approaches and grazing. But the balance and appropriateness of each needs to be considered in terms of location, habitat, impact on C-cycling and plant-landscapes adaptations to fire.

Fire behaviour is also likely to alter, where fire intensity and spread rate may be increased in periods of very high fire weather indices. This means that our Fire and Rescue Services and land managers need to be provided with wildfire specific training if they are to manage future wildfire incidents. It is likely that we will see an increase in the number of fires that cannot be directly attacked, hence training and infrastructure will be required for indirect attack of major wildfire events. The threat of fire at the rural urban interface must be understood and regularly reviewed, this is critical to infrastructure, business and industry and communities and human health. Building codes in these areas and others adjacent to at risk vegetation types, will need to be adjusted to capture fire risk and minimise the impact on built infrastructure and human health. Fire risk should therefore be included in the planning phases of new infrastructure in such causes.

Environmental impacts caused by climate change in respect to wildfire are not fully valued in the National Security Risk Assessment (NSRA), Community Risk Assessments or the Key Capabilities Framework, hence currently the severity and likelihood of wildfire as a natural hazard is underrepresented and the risk rating being undervalued. Likewise, the National Risk register does not value Natural Capital Assets despite the UK's ecosystem services being valued at £761 billion. Fire poses a significant threat to ecosystem services as well as key infrastructure (e.g., major road networks) and water supplies therefore its impacts are wide reaching. Thus, we urge wildfire not to be ignored in major policy documents relating to climate change, land management and national security. These documents must consider fire and climate change with a long-term view, where both policy and stakeholders will need to work together to build our capacity to adapt to these major shifts. Short policy durations (e.g., 3 years) are too short to capture the long-term planning and foresight required to adapt to the changing fire risk over the next 50 years. Our planet has hosted wildfires for some 420 million years; fire cannot and should not be removed, it is a process that maintains the functioning of the Earth system (Belcher et al., 2021). Therefore, it is essential that we learn to live and work with fire in a holistic manner if we are to sustain our landscapes, infrastructure, health and the economy in the decades to come. The following table (Table 2) outlines the impacts and adaptations that are key if we are to make steps forward in understanding and working with the UK's future fire risk. This table links to the evidence presented in Table 1.

Table 1. WILDFIRE BASED ADAPTATION IN THE FACE OF CLIMATE CHANGE				
Evidence Point	Consideration	Issue	Opportunity	CCRA3 Chapter Link
Natural Environment and Assets: Landscape and Fuel Management				
A1, A2, B1, C1, D1	<p>Many of the UK's most fire prone habitats are in areas designated as AONB, SSSI, SPA, SAC or Ramsar sites.</p> <p>Fire risk in these habitats will change in the future based on predictions for the increased % of days experiencing very high fire weather indices, and the trend towards larger burned areas in many of these habitats (e.g., Calluna dominated habitats).</p>	<p>Climatic changes and changes in fuels may lead to changes in fire behaviour. Our fires may become more intense, producing longer flame lengths and more rapid spread that make them inappropriate to tackle with direct approaches (as are common in the UK).</p>	<p>Whatever the land management agenda, the potential alteration to wildfire risk and fire behaviour must be considered, understood and managed at a variety of temporal and spatial scales in these critical habitats.</p> <p>More research is required tailored to UK ecosystems to understand the conditions that lead to ignition and the range of fire behaviour that we may expect in the UK. As this will impact not only the risk but also the appropriate level of civil contingency to be planned. All stakeholders need to be engaged in this process, from researchers to land managers to Fire & Rescue Services (FRS).</p>	<p>Chapter 3 Natural Environment and Assets</p> <p>Chapter 4 infrastructure</p> <p>Chapter 5 Health, Communities, and the Built Environment</p>
A1, A2, D1	<p>Predictions of climate-driven vegetation changes may drive changes in fuel loads and types in a whole range of habits. Coupled to changes in fire weather indices this may alter the fire risk and increase burned area in a range of landscapes.</p>	<p>Not all land defined as a 'priority habitat' are in designated areas for protection.</p> <p>Fuel changes in non-priority habitats may alter fire risk across a myriad of land use classes.</p>	<p>Areas that do not fall into designation classes (e.g., AONB, SSSI, SPA, SAC etc) may not have the same level of protection or detailed land management plans in respect to fuel and fire.</p> <p>Recognition of changes to fire risk across a wide range of land use categories will be required. Particularly in landscapes that have the potential to experience large fires and in landscapes that adjoin key infrastructure or housing.</p>	<p>Chapter 3 Natural Environment and Assets</p> <p>Chapter 4 infrastructure</p> <p>Chapter 5 Health, Communities, and the Built Environment</p>
D1, E1	<p>Predictions of climate-driven vegetation changes suggest that in some parts of the UK an increase in woody fuels may occur at the expense of grasses fuels. Whilst other areas will see up to a 30% increase in fuel load. This is likely to lead to increases in burned area (Wu et al., 2015).</p>	<p>There is a lack of detailed forecasting of climate-driven vegetation changes for the UK. Most information is from global models that include the UK.</p> <p>Shifts in vegetation type and fuel load will need to be considered in terms of impacts on existing habitats and their role in future ecosystem maintenance and services. Maintaining existing habitats may not always be the most appropriate route for maintaining ecosystem health at all sites. Either in terms of health, ecosystem services, carbon-storage or wildfire risk, as well as assessing the challenges that changes may bring in terms of fire-fighting.</p>	<p>Unfortunately, there are no good UK-based scale predictions of climate-driven vegetation changes. Research is required that focusses on building model simulations to look at changes in fuel and fire across the UK spatial scale.</p> <p>Shifts in vegetation type and structure and fuel load will need to be assessed through a long-term planning lens with a holistic view.</p> <p>In terms of wildfire, climate-driven changes to vegetation may be positive in terms of making some habitats more wildfire resilient by breaking up fuel continuity (Calkin et al., 2013) and providing FRS with opportunities to suppress or generate tactical burn opportunities.</p>	<p>Chapter 3 Natural Environment and Assets</p>

A1, A2, D1	A growing area of public, academic and policy interest is that of rewilding (e.g., Alison and Wentworth, 2016, Carver, 2017). Rewilding can be thought of reinstating natural processes to address the continuum of human modification of landscapes over recent decades and centuries. Of major relevance to climate-change is the rewilding of degraded natural landscapes, with the aim to store and capture greenhouse gas emissions.	Restoring degraded landscapes in particular may have large scale implications for alteration of fuel loads (amount and type) that will alter landscape wildfire risk in the UK	<p>There needs to be recognition that wildfire risk should be considered over a range of re-wilding scales. Large landscape rewilding schemes will need assessments that look at both ignition potential and fire behaviour, so that FRS and land managers can be prepared for altered fire regimes.</p> <p>Small scale re-wilding schemes, that adjoin existing landscapes, may still have significant ability to alter ignition potential, and therefore, wildfire risk requires consideration across all scales of re-wilding approaches.</p> <p>Hence clarification of scale in re-wilding terminology is important if we are to capture the range of possible land use and land management possibilities in respect to changing fire risk due to re-wilding and the impact of coupled climate change on altered ecosystems</p>	Chapter 3 Natural Environment and Assets
A1, A2, D1, E1	The target set by the UK government in 2019 to achieve 'net zero' emissions by 2050 requires reductions of 15.5 MtCO ₂ per year over the next 30 years (Committee on Climate Change, 2020). As part of the range of options available to meet these targets, changes to land uses across the UK have been proposed to facilitate greenhouse gas removal from the atmosphere, which include increases in tree planting, restoration of peatland, and encouragement of bioenergy crops (Committee on Climate Change, 2020).	Changes to land use could have the potential to change the fuel loading, such as increases in above-ground fuel following afforestation or shifts in species assemblages following rewetting of peatlands. These changes can both increase and decrease fire risk, depending on the nature of the fuel changes.	<p>In any management scenario, wildfire risk should be considered and be reviewed throughout any landscape transitions surrounding 'net zero' carbon sequestration plans.</p> <p>Wildfire needs to be placed into the minds of planners, developers, conservation, forestry and land management in the land use agenda. This should be both in terms of:</p> <ol style="list-style-type: none"> 1) impact on carbon sequestration due to wildfire impacts - particularly in respect to peatland fires being a net carbon source if peat soil is destroyed by fire 2) enhanced fire risk or a change in fire behaviour that could make fires more difficult to control, due managed vegetation change, climate-driven vegetation change and changes in the seasonality and likelihood of shifts in conducive fire weather. 	<p>Chapter 3 Natural Environment and Assets</p> <p>Chapter 4 infrastructure</p> <p>Chapter 5 Health, Communities, and the Built Environment</p> <p>Chapter 6 Business and Industry</p>
A1, A2, C1, D1	Fire has been used as a land management tool for centuries in the UK, where Heather dominated ecosystems, such as moorlands and heathlands tend to be those that have most consistently been managed using fire.	We do not have the information and evidence required to assess full ecosystem impacts in terms of habitat and species diversity in relation to well-designed prescribed fires nor the effects of the removal of fire as a management tool.	<p>Much local knowledge is held by traditional land practitioners. However, these approaches are at risk due to climate change.</p> <p>All current practices need to be assessed in terms of adjustments to risk in a</p>	Chapter 3 Natural Environment and Assets

	<p>Changing fire weather indices, fuel loads and fire risk will influence how we use fire as a land management tool.</p> <p>The removal of fire from some of landscape may have negative impacts for fuel loads.</p>		<p>changing climate. Adaptation of traditional practices will be required.</p> <p>All stakeholders need to work together towards building true fire prescriptions as fire should be kept in the land management toolbox.</p> <p>Equally any considerations of fire removal need to build understanding of the long-term impacts of this on our key ecosystems.</p>	
A2, C1, E1	<p>Heather is one of the dominant fuel types in the UK's fire prone ecosystems and is being increasingly understood to be not only fire tolerant but, it also appears to be becoming fire adapted where fire has been used as part of anthropogenic management over long periods. Recent research indicates that the seeds of heather in fire managed landscapes appear to respond more to smoke stimulation by fire and germinate and regrow more quickly after fire.</p> <p>This may be a valuable plant trait in maintaining such habitats based on the predictions of a larger percentage of summer days being conducive to fire and larger burned areas becoming more likely.</p>	<p>It has been suggested that burn rotations should be >15 years in UK moorlands (Defra, 2007) (in non-designated sites) and even banned (Defra, 2021). However, the time between burn rotations is much debated and varies based on local conditions and vegetation regrowth (Harper et al., 2018); both in terms of species and regrowth rate (fuel load). Likewise, there is not enough information on what removal of fire will do to the landscape.</p> <p>Studies that include assessing the influence of rotational burning on C-emissions, which is important under the UK's net zero emission agenda, has suggested that heather dominated ecosystems in the UK require different rotational burning from north to south. Where for northern sites the optimal rotation interval is between 30-50 years (limited fire) and for southern sites either between 8-10 years (frequent fire) at least in terms of minimising carbon emissions from 'prescribed' fires and therefore mitigating any potential net contribution of carbon to the atmosphere</p>	<p>Heather's fire adaptations may aid the ability of our managed heather dominated ecosystems to survive shifting fire regimes into our globally warm future. i.e., they may be preadapted to high fire frequency.</p> <p>Hence the continued and expanded management of heather using prescribed fire appropriately both in terms of habitat maintenance and fuel management likely continues to be pertinent. Both in terms of fuel management to mitigate the increased large wildfire risk but also to keep this habitat healthy.</p> <p>More research is needed on appropriate land management styles across the UK's latitudes and heather-based ecosystems and the development of real data from prescribed fire as part of burn rotations to add science-based fire practices into fuel and landscape management practices.</p>	Chapter 3 Natural Environment and Assets
A1, A2, C1, E1	<p>Currently, prescribed fires can be undertaken between 1st October-15th April in England, 1st October – 31st March in Wales, 1st October and 30th April in Scotland and between the 1st September and 14th April in Northern Ireland. It is estimated that just 0.6% of the total cover of upland areas are burnt each year, and it has been argued that these dates do not allow enough fuel clearance using fire due to the high variability of weather in the UK between Autumn and Spring. This issue is likely to be exacerbated by the increase in days with very high fire weather indices in early spring (Fig. D1a)</p>	<p>Many prescribed fire teams (be they land management, private or FRS led) are not able to meet their planned habitat protection and fuel management quotas within the allotted time window, which leads to significant increases in fuel loads in fire prone ecosystems.</p> <p>This issue could become problematic in the near future as the number of days experiencing high fire weather indices (Fig. D1a) in terms of prescribed fire season and the significant increase in very high fire weather indices in the summer will make uncleared heavy fuel loads a significantly greater risk (Fig. D1b, D2). Therefore, larger, difficult to action wildfires are likely to result. If this occurs in peat-based ecosystems this may lead to a net contribution of carbon to the atmosphere, which will have significant implications for the net zero targets.</p>	<p>An increase in the capacity of personnel able to undertake prescribed fires is needed and requires significant investment in effective training for FRS specialist teams, land managers and foresters. This will enable the safe and beneficial removal of fuel loads in fire prone habitats where it is safe to do so.</p> <p>Investment in building competence and maintaining skills of crews is required and partnerships need to be extended between FRS, land management and forestry agencies as well as local landowners to enhance the benefit of managing fuel loading on the landscape using prescribed fire in order to lower the risk of large wildfires as we face</p>	Chapter 3 Natural Environment and Assets Chapter 4 infrastructure

			the UK's climate change challenges.	
A1, A2, D1	The predicted increase in the percentage of days experiencing very high fire weather (Fig. D1) along with suggestions of climate-driven vegetation changes (Fig. D9) means fuel types and loads will be required to be monitored and managed throughout the year to prevent large high-severity wildfires.	<p>Mechanical fuel treatments have much longer seasons of operation. They need not be confined to specific months with the exception of effects on nesting birds and other conservation specific remits.</p> <p>Mechanical fuel treatments can be operated in summer months therefore can be used outside of the prescribed fire season to mitigate any additional spring green up.</p>	<p>It is likely that mechanical operations will need to be extended into the future to manage fuel loads year-round.</p> <p>Alterations to fire risk should be considered when planning mechanical fuel removal e.g., masticated fuel beds for example likely enhance fire risk. So mechanical approaches require a clear design as to the intended incomes.</p> <p>More research is required to assess the long-term implications of mechanical practices in some habitats, for example mowing and turf cutting can affected a considerable amount of the organic soil profile and have negative consequences for carbon storage.</p> <p>Additional investment in terms of infrastructure and trained personnel will be required to enhance any mechanical means to manage fuel loads to mitigate the enhanced fire risk.</p>	Chapter 3 Natural Environment and Assets
B1, C1	Mitigation of the apparent periodicity of large wildfires in the UK and the trend over the last three years of fires attaining large burned areas are anticipated to continue into the future, indicating that large areas of land may require fuel management strategies.	<p>Net costs for mechanical treatments are generally higher than those of prescribed fire, particularly at the landscape scale. This may not be true for small units as prescribed fires on small plots can require as much infrastructure as large burn units</p> <p>Mechanical fuel treatments are difficult to operate at the landscape scale and difficult to operate on slopes.</p> <p>Some mechanical practices, e.g., heavy machinery, use fossil fuels so remain a net-carbon contributor to the atmosphere.</p>	<p>More research is required in UK ecosystems to compare the efficacy of mechanical versus fire-based fuel management. More research is required into cost-benefits of mechanical versus fire-based fuel management practices.</p> <p>Additionally, other fuel management practices may need expansion. Grazing for conservation and fuel management should be supported by recognising higher quality animal products obtained from animals grazing in fire-prone landscapes, particularly where hardy, rare breeds are used.</p> <p>Addition or re-addition of grazing practices and/or prescribed fire should be considered where large areas of fuel removal are required.</p> <p>This highlights the importance of the need to consider multiple factors and carrying out careful risk assessment when managing land large areas against wildfire threats.</p>	Chapter 3 Natural Environment and Assets

Natural Environment and Assets: Socio-Economic and Policy Aspects				
A1, A2, C1, D1	Trends in increasing burnt area over the last three years, combined with predicted increases in the days experiencing very high fire weather indices suggest that wildfire is likely to be relevant to multiple stakeholders requiring coordination in their wildfire risk planning and responses	Wildfire has been considered in many legislative actions, however, many of the key acts of parliament do not work well together to produce the best outcomes for wildfire incident mitigation or risk planning Legislation typically works over political cycles, and these are not long-enough to consider long-term climatic drivers of wildfire and habitat planning.	Both the National Security Risk Assessment and the Community Risk Assessment should link to the Climate Change Risk Assessment timescales to ensure long-term vision is provided to guarantee adaptation to natural hazards, such as wildfire, in fire, land management and forestry sectors and treated as high level risks to allow significant treatment measures over the long-term (e.g., decadal to multi-decadal timescales).	Chapter 3 Natural Environment and Assets Chapter 4 infrastructure Chapter 5 Health, Communities, and the Built Environment
A1, A2	Following the UK exit from the European Union, new agricultural policy will be rolled out to replace elements of the Common Agricultural Policy (CAP).	Any long-term changes to land use could have important impacts on how fuels accumulate, with consequent impacts for wildfire. These changes will need to be balanced against predictions for changes in fire weather indices over the next 40 years	Scenario development for future land use is a key approach to exploring complex trade-offs and must include recognition of changing wildfire threats given commitment to international treaties. Research will be needed to consider how agriculture changes in land-use and crop type and their positioning in respect to other open or managed habitats, will alter risk and fire behaviour.	Chapter 3 Natural Environment and Assets Chapter 5 Health, Communities, and the Built Environment Chapter 6 Business and Industry
D1, E1	Land management changes that are designed to enhance carbon capture, such as afforestation schemes, restoration of peatland, the planting of bioenergy crops. As well as large-scale rewilding schemes that aim to re-wild degraded landscapes through to smaller schemes that may influence fuel closer to infrastructure may alter wildfire risk both in terms of changes to fuel and due to the predicted increase in very high fire weather indices.	The wildfire risk may be increased or decreased depending on the nature of the scheme. Each approach taken will not only have significantly different greenhouse gas mitigation potential but also a wide range differences in the associated wildfire risk and potentially different wildfire feedbacks to climate. The range of different approaches captured under the term 'rewilding' means that there is certainly no generalised approach to assessing the changes in wildfire risk associated with this approach.	It is essential that ecosystem-based carbon capture schemes pay attention to the possible change in fire risk due to the alteration of fuel type. Variations in fire risk will need to be considered for each phase of vegetation structure i.e., ecological succession, so the implications for intermediate and final habitat developments may need separate wildfire risk considerations. Wildfire may be enhanced at some points and decreased at others. Small schemes that are close to housing and infrastructure should also be considered in terms of altering ignition based on fuel and how this risk might change in response to increased likelihood of very high fire weather indices.	Chapter 3 Natural Environment and Assets Chapter 5 Health, Communities, and the Built Environment Chapter 6 Business and Industry
Infrastructure: Civil Contingency				
A1, A2, C1, D1	Changing wildfire risk due to increased percentage of days experiencing very high fire weather indices, vegetation change and land management decisions will impact the civil contingency required to manage resulting wildfires. This is particularly concerning in regard	Each Fire and Rescue Service determines its response priorities based on a risk assessment; in England this is known as the Integrated Risk Management Plan (IRMP). Following analyses of FRS IRMPs, ~50% of FRS in the UK have	National FRS Frameworks in England, Wales, Scotland and Northern Ireland must consider wildfire in their IRMPs and for Fire and Rescue. This will, however, require land management decisions and information to be passed to the FRS. Such	Chapter 3 Natural Environment and Assets Chapter 4 infrastructure

	to recent trends in larger burnt areas.	noted officially an awareness of wildfire as a risk in their region but only 10% have an awareness in terms of forward planning for climate-driven increases in wildfire threat. This limits our potential to mitigate the increased occurrence of large wildfires and adapt in the face of climate-shifted fire regimes.	that planning and advice on wildfire can be made in partnership with land management and forestry agencies, working at local, landscape and regional scales. The IRMP assessment should then be made public in an accessible format so informed land use planning decisions can be made to manage any social and infrastructural threats due to wildfire. Additionally, individual IRMPs will need sharing throughout FRS allowing all to enhance their preparedness and ability to assist with large wildfires outside of their region as is often required at large events (e.g., Saddleworth Moor 2018).	Chapter 5 Health, Communities, and the Built Environment Chapter 6 Business and Industry
A2	Some regions will see greater than 20% of summer days reaching conditions of very high fire weather index in the next 30 years (Fig. D4). Hence forward planning is required if Fire and Rescue Services are to be prepared, appropriately trained and equipped.	Currently the National Framework 2008-2011 requires each Fire and Rescue Authority to produce an IRMP covering a minimum of a 3-year time span. A 3-year time periods is too short-term to capture the long-term planning required to adapt FRS approaches to the predicted changing fire regimes over the coming decades. IRMPs play a critical role in determining allocation of resources for FRS These issues are important because each Fire and Rescue Service determines its response priorities based on a risk assessment; in England this is the Integrated Risk Management Plan (IRMP). This then determines the location of resources, the equipment and training received by each individual FRS.	Immediate and long-term wildfire risk plans should be required to be included in FRS IRMPs. The lack of wildfire in a substantial fraction of FRS IRMPs implies that at least half of the UKs FRS will not have been provided with wildfire specific Personal Protective Equipment (PPE), or specialised wildfire training at this point in time. Practical accredited training is required in wildfire suppression and fuel management. This should include the management of high and extreme fire intensity such as aerial means and indirect attack. This should be available to both FRS and land management stakeholders. Hence where wildfire is identified as a significant risk within an FRS IRMP then, consideration should be given as to the provision of appropriate wildfire PPE, training and equipment.	Chapter 3 Natural Environment and Assets Chapter 4 infrastructure Chapter 5 Health, Communities, and the Built Environment
D1	Changes in fuel type, be it from land management strategies or climatic drivers will have joint implications for land managers, stakeholders and FRS in terms of building wildfire preparedness strategies.	The Communities and Local Government IRPM policy guidance document (2008) states that 'In aiming to successfully deliver wildfire strategies the FRS will need to work in partnership with other stakeholders.' Each FRS needs to identify the most appropriate stakeholders and generate working relationships effectively together to deliver the shared goals of a wildfire strategy.	These areas would benefit from further research and knowledge exchange regarding best practice. It may be that integrated system to allow coordination of wildfire response in the form interagency working could be of utility.	Chapter 3 Natural Environment and Assets Chapter 4 infrastructure Chapter 5 Health, Communities, and the Built Environment

		<p>There are several ad-hoc arrangements in place to encourage close working between FRS and other agencies such as the Wildfire Forums and the Fire Operations Groups (FOGs).</p> <p>There are no nationally agreed protocols to enable joint working and this may add to the uncertainty around the risk of tackling wildfires.</p>	<p>Large wildfire incident management would benefit from the provisions of training scheme and standard protocols that would allow the fire, land management and forestry sectors to ensure interoperability during incidents.</p> <p>The National Coordination and Advisory Framework (NCAF) could be a high-level starting point for managing large scale major incidents.</p>	Chapter 6 Business and Industry
C1	<p>The apparent trend of increasing burned areas and the regular periodicity of fires occurring that have large burned areas calls for additional training provision to FRS and land managers in terms of managing large wildfires.</p> <p>Additionally, it is likely that fire behaviour will change, with the UK seeing more extreme fires in the future.</p>	<p>These fires will have longer flame lengths and spread will likely be more rapid.</p> <p>Tactical burning can be used effectively as part of an operational response. It can provide, among others, the following benefits:</p> <ul style="list-style-type: none"> - Reduction in the time taken to extinguish a wildfire and mitigate the burned area attained and their severity. - Reduction in the overall number of personnel and appliances required at an incident, reducing response costs. - Increase capacity of personnel including land manager and forestry organisations. - Improved firefighter, land manager and public safety. 	<p>Indirect attack approaches which are required when flame lengths are greater than 2.5m will likely be required to be enhanced.</p> <p>Approaches such as aerial attack and tactical burning will need to be increasingly considered, such as those used at Wareham Forest, May 2020.</p> <p>Therefore, provisions must be made to train FRS, land managers and foresters in the management of high intensity fires and in tactical burn training.</p> <p>This will need to be provided in fire-prone landscapes (and those identified by IRMPs), if not nationally owing to enhanced capacity requirements for an increase in the frequency of large fire events.</p> <p>This links to the NFCCs Wildfire Tactical Advisor whom could serve as leaders for trained tactical burn teams.</p>	Chapter 3 Natural Environment and Assets
A1, A2, B1	Nearly all UK wildfire ignitions are anthropogenic. Increased occurrence of very high fire weather indices suggests that the public need to be engaged in order to decrease behaviours that might lead to ignition during periods of high fire risk.	The UK does not routinely investigate the cause of wildfire ignitions and has no Fire Investigators qualified in this specialist skill.	Enhancement of social understanding of wildfire is required and the development of an appropriate fire danger rating system linked to a public communication arm of the system	Chapter 3 Natural Environment and Assets Chapter 4 infrastructure Chapter 5 Health, Communities, and the Built Environment
Infrastructure: Health, Services and the Built Environment				
A1, A2, D1	The majority of large (>30ha) fires occur in semi-natural vegetated habitats across the UK, although frequent fires occur in a variety of environments from semi-natural habitats to urban patches of grassland. A great proportion of fires affect vegetated areas in close proximity	A challenge lies with the intermixing of high-risk wildland/semi-natural fuels and the built environment which increases the risk of ignition and, also, disruption, damage to and/or destruction of property and threatening lives	Building codes, such as Approved Document B and egress plans for housing estates, should be included for wildfire risk in the design of new developments at the rural-urban interface in the UK.	Chapter 3 Natural Environment and Assets Chapter 4 infrastructure

	to built-up areas. This places people and infrastructure at risk due to enhanced increases in fire weather indices over the coming decades. Additionally, any changes in fuels due to re-wilding agendas and climate-driven alterations at the rural urban interface and within built up areas may increase ignition risk.	To date, the rural-urban interface wildfire risk has not been considered in UK building regulations and in general building fire safety regulations in the UK only anticipate ignition from the inside and not from that such as ember ingress from wildfires.	Building codes should include guidance for the appropriate layout, building materials as well as emergency access and escape routes planning designed to standards and codes	Chapter 5 Health, Communities, and the Built Environment Chapter 6 Business and Industry
A2, B1, C1	A significant portion of the UKs water supplies rely on reservoir holding and collecting facilities. These tend to be located in green belts or semi natural habitats, with many in fire-prone habitats and regions that may be at increasing risk of ignition and which tend to host wildfires that attain large burn perimeters.	Wildfires can cause considerable issues for water storage and supplies where reservoirs are situated in regions where large burned areas may be attained. The Saddleworth Moor wildfire in 2018 led to drainage of some reservoirs in the area before contamination could occur. The costs of actioning the fire and subsequent land restoration were a significant cost to the land owner.	There is good evidence that undertaking wildfire risk assessments for land hosting such infrastructure and putting in place necessary mitigation strategies for cost avoidance of future extensive wildfires. Land and infrastructure owners should be encouraged to undertake risk assessments and update infrastructure and undertake land management strategies to protect such assets in the case of wildfires	Chapter 4 infrastructure Chapter 5 Health, Communities, and the Built Environment Chapter 6 Business and Industry
A2	The UK's major road infrastructure, i.e., motorways, are situated in the regions where the greatest increases in the % of very high fire weather indices are forecasted.	Closure of major roads in a wildfire emergency, either due to smoke or rerouting due to proximity to wildfire would have major cost implications.	Wildfire risks around major road infrastructure will need review over the coming decades (this was likely last done for the 2012 Olympics), and consideration as to additional protection and road closure mitigation plans prepared to avoid costly road closures and losses to the economy.	Chapter 4 infrastructure Chapter 5 Health, Communities, and the Built Environment Chapter 6 Business and Industry Chapter 7 International Dimensions
A1, A2, C1, D1	Ecosystems provide services to society in a number of ways which are estimated currently as being worth some £761 billion in the UK. Wildfire impacts not only include impacts on human health but on assets held within ecosystems such as timber and agricultural biomass, water extraction and storage and peat-based carbon sequestration will be severely at risk from enhanced fire weather and therefore chance of ignition and the trend to large burned areas. As well as due to climate and management driven changes fuel.	Currently the National Risk Register does not value Natural Capital Assets. Hence it is difficult to recognise the value of funding that works towards wildfire mitigation, prevention and protection of carbon sequestration.	The net gain in resource protection via investment in animal-, fire- and mechanical-based fuel practices will need to be assessed in order to protect ecosystem services. Therefore, being able to account for the value of carbon lost by wildfires e.g., damage to forestry stocks or peatlands through to the increase in hospital admissions due to large-scale smoke events (e.g. Saddleworth, 2018) allows these costs to be weighed against the costs of preventative options for managing the risk ahead of time.	Chapter 3 Natural Environment and Assets Chapter 4 infrastructure Chapter 5 Health, Communities, and the Built Environment Chapter 6 Business and Industry
A1, A2	The large number of fires that occurs in built-up areas and gardens pose a significant risk to life, properties and infrastructure assets. The risk of ignition in these situations is likely to increase in terms of ease of ignition in the coming decades.	At least 2 Firewise communities have been set up in fire prone areas of the UK (linked to the US NFPA Firewise scheme).	Support for such community led schemes that allows property owners to make homes and gardens more resistant to wildfires should be supported and encouraged by local FRS and government schemes.	Chapter 5 Health, Communities, and the Built Environment

<p>A1, A2, C1, D1</p>	<p>As part of both environmental and health agendas, there has been a push by successive governments, as well as charities and third sector organisations to encourage greater engagement with the natural world.</p> <p>Increased access and visits to green spaces, particularly in the urban and peri-urban environments, can potentially lead to increased occurrences of ignitions due to more people visiting natural spaces. In addition, the change of ignition will also be heightened due to an increased % of very high fire weather indices during warm spring days and the summer months.</p>	<p>General lack of understanding of wildfire risk and the dangers and implications of wildfires.</p>	<p>Preventative measures (e.g., public information campaigns at times of high fire risk), as well as increased monitoring of human activities in at risk areas during the fire season will be required.</p> <p>Enhancement of social understanding of wildfire is required and the development of an appropriate fire danger rating system linked to a public communication arm of the system</p>	<p>Chapter 3 Natural Environment and Assets</p> <p>Chapter 5 Health, Communities, and the Built Environment</p>
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References

- Agee, J.K., Skinner, C.N., (2005) Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* 211, 83–96. doi:10.1016/ J.FORECO.2005.01.034.
- Albertson K, Aylen J, Cavan G, McMorrow J (2010) Climate change and the future occurrence of moorland wildfires in the Peak District of the UK. *Clim Res* 45:105-118. <https://doi.org/10.3354/cr00926>
- Alderson, D.M., and six others (2019) Trajectories of ecosystem change in restored blanket peatlands. *Science of The Total Environment*, 665, 785-796.
- Alison, J. and Wentworth, J. (2016) Rewilding and ecosystem services. POSTnote 537. <https://post.parliament.uk/research-briefings/post-pn-0537/>
- Allen, K.A., Denelle, P., Sanchez-Ruiz, F.M.S., Santana, V.M. and Marrs R.H. (2016) Prescribed moorland burning meets good practice guidelines: a monitoring case study using aerial photography in the Peak District, UK. *Ecological Indicators*, 62, 76-85.
- Arganaraz, J., Landi, M.A., Scavuzzo, C.M. and Bellis, L.M. (2018) Determining fuel moisture thresholds to assess wildfire hazard: A contribution to an operational early warning system. *PLoS one*, 13, e0204889. <https://doi.org/10.1371/journal.pone.0204889>.
- Arnell, N.W., Freeman, A. and Gazzard, R. (2021) The effect of climate change on indicators of fire danger in the UK. *Environmental Research Letters*, 16, 044027.
- Aylen, J., Cavan, G., McMorrow, J., 2011. Costing wildfires. *Wildfire 2011*, 14/Sep/2011–15/Sep/2011, Buxton, Derbyshire, UK. <http://www.ruraldevelopment.org.uk/files/rdi/Costing%20the%20Spring%202011%20Wildfires.pdf>.
- Aylen, J., McMorrow J., Kazmierczak, A., Gazzard, R., Cavan, G. (2015) *Wildfire Impacts – Costs and Risks*. Swinley Wildfire Seminar, Greenwich.
- Baker, S.J., Belcher, C.M., Barclays, R.S., Hesselbo, S.P., Laurin, J. and Sageman, B.B. (2019) CO₂-induced climate forcing on the fire record during the initiation of Cretaceous oceanic anoxic event 2. *GSA Bulletin*, 132, 321-333.
- Belcher, C.M., Mills, B.J.W., Vitali, R., Baker, S.J., Lenton, T.M. and Watson, A.J., (2021) The rise of angiosperms strengthened fire feedbacks and improved the regulation of atmospheric oxygen. *Nature Communications*, 12, 503.
- Busch, M., La Notte, A., Laporte, V. and Erhard, M. (2012). Potentials of quantitative and qualitative approaches to assessing ecosystem services. *Ecological Indicators*, 21, 89-103.
- Carver, S. (2017) #Rewilding loving or loathing. *ECOS* 38 (6) <https://www.ecos.org.uk/ecos-38-6-rewilding/>
- Cervera, T., Pino, J., Marull, J., Padro R. and Tello, E. (2016) Understanding the long-term dynamics of forest transition: From deforestation to afforestation in a Mediterranean landscape (Catalonia, 1868-2005). *Land Use Policy*, 80, 318-331.

Climate Change Act, 2008. The UK government, 2008. *Climate Change Act 2008*. London: The Stationery Office Limited. <https://www.legislation.gov.uk/ukpga/2008/27/contents>
Committee on Climate Change, (2020) Reducing UK emissions: 2020 progress report to parliament. <https://www.theccc.org.uk/publication/reducing-uk-emissions-2020-progress-report-to-parliament/>

Climate Data Store (2020) <https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-fire-historical?tab=overview>

Communities and Local Government IRPM policy guidance document (2008) IRMP Steering Group Integrated Risk Management Planning: Policy Guidance – Wildfire. <https://www.gov.uk/government/publications/integrated-risk-management-planning-guidance-for-fire-and-rescue-authorities-wildfire>

Copernicus Climate Change Service (2017). <https://cds.climate.copernicus.eu#!/home>

Curnow, J. (2019) Environmental economics in UK environmental policy: Defra's 25 Year Environment Plan, *Journal of Environmental Economics and Policy*, 8:4, 353-358, DOI: 10.1080/21606544.2019.1601135

Davies, G.M. and Legg, C.J. (2008). The effect of traditional management burning on lichen diversity. *Applied Vegetation Science*, 11, 529-538.

Davies, G.M. and Legg, C.J. (2011) Fuel moisture thresholds in the flammability of *Calluna vulgaris*. *Fire Technology*, 47, 421-436.

Davies, G.M. and Legg, C.J. (2016) Regional variation in fire weather controls the reported occurrence of Scottish wildfires. *PeerJ* 4, e2649.

Davies, G.M., Gray, A., Rein, G. and Legg, C.J. (2013) Peat consumption and carbon loss due to smouldering wildfire in a temperate peatland. *Forest Ecology and Management*, 308, 169-177.

Davies, G.M., Ketteridge, N., Stoof, C.R., Gray, A., Ascoli, D., Fernandes, P.M., Marrs, R., Allen, K.A., Doerr, S.H., Clay, G.D., McMorrow, J. and Vandvik, V. (2016). The role of fire in UK peatland and moorland management: the need for informed, unbiased, debate. *Philosophical Transactions of the Royal Society B*, 371, 20150342.

Davies, G.M., Legg, C.J., Smith, A.A. And MacDonald, A.J. (2009) Rate of spread of fires in *Calluna vulgaris*-dominated moorlands. *Journal of Applied Ecology*, 46, 1054-1063.

Davies, G.M., Smith, A.A., MacDonald, A.J., Bakker, J.D. and Legg, C.J. (2010). Fire intensity, fire severity and ecosystem response in heathlands: factors affecting the regeneration of *Calluna vulgaris*. *Journal of Applied Ecology*, 47, 356-365.

de Jong, M.C., Wooster, M.J., Kitchen, K., Manley, C.M., Gazzard, R. and McCall, F.F. (2016) Calibration and evaluation of the Canadian Forest Fire Weather Index (FWI) System for improved wildland fire danger rating in the United Kingdom. *Natural Hazards in Earth System Science*, 16, 1216-1237.

Deane, P.J., Wilkinson, S.L., Moore, P.A. and Waddington, J.M., 2020. Seismic Lines in Treed Boreal Peatlands as Analogs for Wildfire Fuel Modification Treatments. *Fire*, 3(2), p.21.

Deaton, L. (2017). Getting Out – Tragedies in Portugal and elsewhere demonstrate the complexity and necessity of wildfire evacuation plans. *NFPA Journal*, September 2017.

DEFRA (2007) The Heather and Grass Burning Code. pp. 24. Defra, London.

DEFRA (2010) Assembling UK wide Data on Soil Carbon (and greenhouse gas) in the Context of Land Management. pp. 83. Defra, London.

Dixon, S.G. and Chandler, D. (2019). Producing a risk of sustained ignition map for the Peak District National Park. *Moors for the Future Report*, Edale.

Emmerton, C.A. and thirteen others (2020) Severe western Canadian wildfire affects water quality even at large basin scales. *Water Research*, 183, 116071.

Fernandes, P. (2013) Forest fuel management for fire mitigation under climate change. In book: *Forest Management of Mediterranean Forest Under the New Context of Climate Change: Building Alternatives for the Coming Future* (pp.31-41).

Finney, M.A., Cohen, J.D., McAllister, S.S. and Jolly, W.M. (2013). On the need for a theory of wildland fire spread. *International Journal of Wildland Fire*, 22, 25-36.

Fire Act 2005 – Scotland <https://www.legislation.gov.uk/asp/2005/5/contents>

Fire and Rescue Services Act (2004) England and Wales
<https://www.legislation.gov.uk/ukpga/2004/21/contents>

Fire and Rescue Services Order 2006 - Northern Ireland
<https://www.legislation.gov.uk/nisi/2006/1254/contents>

Forestry Commission England (2019) *Wildfire Statistics for England 2009-10 to 2016-17*. Bristol: Forestry Commission England, 60 pages.

Forestry Commission, 2014. *Building wildfire resilience into forest management planning*. Forestry Commission Practice Guide, Forestry Commission Edinburgh.

Frolking, S., Roulet, N.T., Tuittila, E.S., Bubier, J.L., Quillet, A., Talbot, J. and Richard, P.J.H., 2010. A new model of Holocene peatland net primary production, decomposition, water balance, and peat accumulation. *Earth System Dynamics*, 1, 1-21.

Fyfe, R.M., Brown, A.G. and Rippon, S.J. (2003) Mid-to late-Holocene vegetation history of greater Exmoor, UK: estimating the spatial extent of human-induced vegetation change. *Vegetation History and Archaeobotany*, 12, 215-232.

Gazzard, R, McMorrow, J and Aylen, J. (2016) Wildfire policy and management in England: an evolving response from Fire and Rescue Services, forestry and cross-sector groups. *Phil. Trans. R. Soc. B*, **371**, 20150341 <http://doi.org/10.1098/rstb.2015.0341>

Giglio, L., Boschetti, L., Roy, D.P., Humber, M.L., and Justice, C.O. (2018) The collection 6 MODIS burned area mapping algorithm and product. *Remote Sensing of the Environment*, **217**, 72-85.

Glaves, D., Morecroft, M., Fitzgibbon, C., Owen, M., Phillips, S. and Leppit, P. (2013) The effects of management burning on upland peatland biodiversity, carbon and water. Natural England Evidence Review NEER004. ISBN 978-1-78354-004-4

Glaves, D.J. and Haycock, N.E. (2005) Science panel assessment of the effects of burning on biodiversity, soils and hydrology. Report to Defra Conservation, Uplands and Rural Europe Division, Upland Management Branch.

Glaves, D.J., Crowle, A.J.W., Bruemmer, C. and Lenaghan, S.A. (2020). The causes and prevention of wildfire on heathlands and peatlands in England. Natural England Wildfire Evidence Review NEER014. Peterborough: Natural England. ISBN 978-1-78354-567-4

Glitzenstein, J.S., Streng, D.R., Achtemeier, G.L., Naeher, L.P., Wade, D.D. (2006) Fuels and fire behaviour in chipped and unchipped plots: implications for land management near the wildland/urban interface. *Forest Ecology and Management* **236**, 18–29.
doi:10.1016/J.FORECO.2006.06.002.

Graham, A.M. and sixteen others (2021) Impact of the June 2018 Saddleworth Moor wildfires on air quality in northern England. *Environmental Research Communications*, **2**, 031001.

Graham, A.M., Pope, R.J., McQuaid, J.B., Pringle K.P., Arnold, S.R., Bruno, A.G., Moore, D.P., Harrison, J.J., Chipperfield, M.P., Rigby, R., Sanchez-Marroquin, A., Lee, J., Wilde, S., Siddans, R., Kerridge, B.J., Ventress, L.J., Latter, B.G. (2020) Impact of the June 2-18 Saddleworth Moor wildfires on air quality in northern England. *Environmental Research Communications*, **2**, 031001.

Granath, G., Moore, P.A., Lukenbach, M.C. and Waddington, J.M. (2016) Mitigating wildfire carbon loss in managed northern peatlands through restoration. *Scientific Reports*, **6**, 28498.

Grant, M.C., Mallard, J., Leigh, S. and Thompson, P.S. (2010) The Costs and Benefits of Grouse Moor Management to Biodiversity and Aspects of the Wider Environment: A Review, RSPB, Sandy, UK.

Grau-Andres, R., Davies, G.M., Waldron, S., Scott, E.M. and Gray, A. (2017) Leaving moss and litter layers undisturbed reduces the short-term environmental consequences of heathland managed burns. *Journal of Environmental Management*, **204**, 102-110.

Harper, A.R., Doerr, S.H., Santin, C., Froyd, C.A. and Sunnadurai, P. (2018). Prescribed fire and its impacts on ecosystem services in the UK. *Science of the Total Environment*, **624**, 691-703.

HM Government, (2018) A Green Future: Our 25 year plan to improve the environment.

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/693158/25-year-environment-plan.pdf

Hope, C. (2017) Discussion on the Restrictions Imposed by the Legal Prescribed Burn Seasons in the UK (Personal Communication, 3 March 2017)

Hu, Y., and Fernandez-Anez, N., Smith, T. E. L. and Rein, G. (2018) Review of emissions from smouldering peat fires and their contribution to regional haze episodes. *International Journal of Wildland Fire*, 27, 93-312. DOI: 10.1071/WF17084

Ingram, R.C., Moore, P.A., Wilkinson, S., Petrone, R.M. and Waddington, J.M. (2019) Postfire soil carbon accumulation does not recover boreal peatland combustion loss in some hydrogeological settings. *JGR Biogeosciences*, 124, 775-788.

Jones, M. W., Smith, A. J. P., Betts, R., Canadell, J. G., Prentice, I. C., and Le Quéré, C. (2020). Climate Change Increases the Risk of Wildfires: January 2020. *ScienceBrief*.

Kettridge N. and thirteen others (2019) The impact of wildfire on contaminated moorland catchment water quality. *Geophysical Research Abstracts*, 21, 1-1.

Kettridge, N., Turetsky, M.R., Sherwood, J.H., Thompson, D.K., Miller, C.A., Benscoter, Flannigan, M.D., Wotton, B.M. and Waddington, J.M. (2015). Moderate drop in water table increases peatland vulnerability to post-fire regime shift. *Scientific Reports*, 5, 1-4.

Kornakova, M. and Glavovic, B. (2018) "Institutionalising wildfire planning in New Zealand: Lessons learnt from the 2009 Victoria bushfire experience." *Australasian Journal of Disaster and Trauma Studies*, vol. 22, 2018, p. 51+.

Krawchuk, M.A., Moritz, M.A., Parisien, M-A., Van Dorn, J. and Hayhoe, K. (2009) Global Pyrogeography: the Current and Future Distribution of Wildfire. *PLoS ONE* 4(4): e5102. <https://doi.org/10.1371/journal.pone.0005102>

LANTRA, 2010 <https://www.lantra.co.uk/course/basic-wildfire-fighting>

Lee, H., Alday, J.G., Rose, R.J., O'Reilly, J. and Marrs, R.H. (2013) Long-term effects of rotational prescribed burning and low-intensity sheep grazing on blanket-bog plant communities. *Journal of Applied Ecology* 50, 625-635.

Luckenbach, M.C., Hokanson, K.J., Moore, P.A., Devitor, K.J., Kettridge, N., Thompson, D.K., Wotton, B.M., Petrone R.M. and Waddington, J.M. (2015). Hydrological controls on deep burning in a northern forested peatland. *Hydrological Processes*, 29, 4114-4124.

MA (Millennium Ecosystem Assessment). 2005. *Ecosystems and human well-being: synthesis*. Washington, DC: Island Press.

Mariani, M., Holz, A., Velben, T.T., Williamson, G., Fletcher, M-S., Bowman, D.M.J.S. (2018) Climate change amplifications of climate-fire teleconnections in the Southern hemisphere. *Geophysical Research Letters*, 45, 5071-5081.

Marino, E., Hernando, C., Madrigal, J., Diez, C. and Guijarro, M. (2012) Fuel management effectiveness in a mixed heathland: a comparison of the effect of different treatment types on fire initiation risk. *International Journal of Wildland Fire*, 21, 969-979.

Marino, E., Madrigal, J., Guijarro, M., Hernando, C., Díez, C., Fernández, C. (2010) Flammability descriptors of fine dead fuels resulting from two mechanical treatments in shrubland: a comparative laboratory study. *International Journal of Wildland Fire*. 19, 314–324.

McDonough, K., Hutchinson, S., Moore, T., and Hutchinson, J.M.S. (2017) Analysis of publication trends in ecosystem services research. *Ecosystem Services*, 25, 82-88.

McIver, J., Youngblood, A. and Stephens, S.L. (2009) The National Fire and Fire Surrogate study: ecological consequences of fuel reduction methods in seasonally dry forests. *Ecological Applications*, 19, 283-284.

McMorrow J. and Lindley S. (2006) Modelling the spatial risk of Moorland wildfire. *Moors for the Future* small grant AA79419_spg17.

McMorrow, J., Gazzard, R., & Hedley, P. (2015). Wildfire risk in Community Risk Registers (CRR), Integrated Risk Management Plans (IRMP) and Incident Recording System (IRS). In *Wildfires 2015 conference* Glasgow.

Mitchell, D. and Smidt, M. (2019) Costs of Mechanical Fuel Reduction Treatments. In: Manzello S. (eds) *Encyclopaedia of Wildfires and Wildland-Urban Interface (WUI) Fires*. Springer, Cham. 7p. DOI: https://doi.org/10.1007/978-3-319-51727-8_139-1.

Moffat, A.J. and Gazzard, R. (2019) Wildfire adaptation and contingency planning in South East England – implementation of current legislation and policy. *Quarterly Journal of Forestry*, 113, 160-165.

Muirburn Code (2017) *The Muirburn Code. Management of Moorland by Burning and Cutting*. <https://muirburncode.org.uk/>

Murgatroyd, I.R. (2002) *Planning controlled burning operations in forestry*. Technical note, Forestry Commission, ISBN 0-85538-570-7.

National Fire Chiefs Council (2019) *The National Coordination and Advisory Framework (NCAF)* England. Home Office.

Natural England Report NE257 (2010) *England's peatlands: carbon storage and greenhouse gases*. <http://publications.naturalengland.org.uk/publication/30021>

Natural England, (2021) <https://www.gov.uk/government/news/englands-national-rainforests-to-be-protected-by-new-rules>

NFPA (2008) *Fire Protection Handbook*, 20th Edition. <https://catalog.nfpa.org/Fire-Protection-Handbook-20th-Edition-P13860.aspx>

Oxborough N and Gazzard RJ (2011) *Swinley Forest fire*. *Fire Risk Management*, 12-15.

- Page, S.E. and Hooijer, A. (2016) In the line of fire: the peatlands of Southeast Asia. *Proceedings of the Royal Society B*, 371, 20150176.
- Pausas, J.G. and Keeley, J.E. (2019) Wildfires as an ecosystem service, *Frontiers in Ecology and Environment*, 17, 289-295.
- Pearce, H.G., Finney, M., Strand, T., Katurki, M. and Clements, C. (2019) New Zealand field-scale fire experiments to test convective heat transfer in wildland fires. *Proceedings, 6th Fire Behavior and Fuels Conference, "Fuels of Today-Fire Behaviour of Tomorrow"* volume 29.
- Perino, A. and fifteen others (2019) Rewilding complex ecosystems. *Science*, 364, eaav5570. DOI: 10.1126/science.aav5570
- Perry, M.C., Vanvyve, E., Betts, R. A., and Palin, E. J. (2021) Past and future trends in fire weather for the UK, *Nat. Hazards Earth Syst. Sci. Discuss.* [preprint], in review <https://doi.org/10.5194/nhess-2021-143>.
- Prat-Guitart, N., Belcher, C.M., Thompson, D.K., Burns, P. and Yearsley, J.M. (2017) Fine-scale distribution of moisture in the surface of a degraded blanket bog and its effects on the potential spread of smouldering fire. *Ecohydrology*, 10, e1898.
- Prat-Guitart, N., Rein, G., Hadden, R.M., Belcher, C.M. and Yearsley, J.M. (2016) Propagation probability and spread rates of self-sustained smouldering fires under controlled moisture content and bulk density conditions. *International Journal of Wildland Fire*, 25, 456-465.
- Robroek, B.J., Jassey, V.E., Payne, R.J., Martí, M., Bragazza, L., Bleeker, A., Buttler, A., Caporn, S.J., Dise, N.B., Kattge, J. and Zając, K., 2017. Taxonomic and functional turnover are decoupled in European peat bogs. *Nature Communications*, 8(1), pp.1-9.
- Santana VM, Alday JG, Lee H, Allen KA, Marrs RH (2016) Modelling Carbon Emissions in *Calluna vulgaris*-Dominated Ecosystems when Prescribed Burning and Wildfires Interact. *PLOS ONE* 11(11): e0167137. <https://doi.org/10.1371/journal.pone.0167137>
- Santin, C. and Doerr, S.H. (2016) Fire effects on soils: the human dimension. *Philosophical Transactions of The Royal Society B*, 371, 20150171.
- Santosom M.E., Christensen, A.G., Yang, J. and Rein, G. (2019). Review of the transition from smouldering to flaming combustion in wildfires. *Frontiers in Mechanical Engineering*, 5, 49. <https://doi.org/10.3389/fmech.2019.00049>
- Schlobohm, P. and Brain, J. (2002) Gaining and Understanding of the National Fire Danger Rating System. National Wildfire Coordinating Group Publication. <https://www.nwccg.gov/sites/default/files/products/pms932.pdf>
- Scottish Government, (2013) Fire and Rescue Service Wildfire Operational Guidance. ISBN 9781782564980. <https://www.gov.scot/publications/fire-rescue-service-wildfire-operational-guidance/pages/4/>

SEERAD (2001) Prescribed burning on Moorland: Supplement to the Muirburn Code: A Guide to Best Practice. Edinburgh: Scottish Executive.
Shakesby, R.A. and Doerr, S.H. (2016) Wildfire as a geomorphological agent. *Earth Science Reviews*, 74, 269-307.

Simmons, I.G., Innes, J.B. (1987) Mid-holocene adaptations and later Mesolithic forest disturbance in Northern England. *Journal of Archaeological Science*. 14, 4, 385-394, IN1-IN2, 395-403.

Sloan, T.J., Payne, R.J., Anderson, A.R., Bain, C., Chapman, S., Cowie, N., Gilbert, P., Lindsay, R., Mauquoy, D., Newton, A.J. & Andersen, R. (2018): Peatland afforestation in the UK and consequences for carbon storage. *Mires and Peat*, 23(01), 1-17.

Smith HG, Sheridan GJ, Lane PNJ, Nyman P, Haydon S. 2011. Wildfire effects on water quality in forest catchments: A review with implications for water supply. *Journal of Hydrology*, 396(1-2):170-192

Strassburg, B.B.N. and twenty-six others (2020) Global priority areas for ecosystem restoration, *Nature*, 586, 724-729.

Tucker, G. (2003) Review of the Impacts of Heather and Grassland Burning in the Uplands on Soils, Hydrology and Biodiversity. Research Report No. 550. English Nature, Peterborough, UK.

Tuittila, E.S., Vasander, H. and Laine, J., 2000. Impact of rewetting on the vegetation of a cut-away peatland. *Applied Vegetation Science*, 3(2), pp.205-212.

Turetsky, M.R., Benscoter, B., Page, S., Rein, G., van der Werf, G.R. and Watts, A. (2015). Global vulnerability of peatlands to fire and carbon loss. *Nature Geoscience*, 8, 11-14.

UK Government, (2020) Farming for the future – Policy and progress update, PB1460 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/868041/future-farming-policy-update1.pdf

UK Government (2019a) [UK becomes first major economy to pass net zero emissions law. Department for Business, Energy & Industrial Strategy. https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law](https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law)

UK Government. (2019b) Road Traffic Estimates: Great Britain 2018. Department of Transport.

UK Met Office, (2018) https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/state-of-uk-climate/soc_supplement-002.pdf

UKCIP (2018) <https://www.ukcip.org.uk/wizard/future-climate-vulnerability/>

Vandvik, V., Töpper, J.P., Cook, Z., Daws, M.I., Heegaard, E., Mären, I.E. and Velle L.G. (2014) Management-driven evolution in a domesticated ecosystem. *Biology Letters*, 10, 20131082.

Welsh Assembly Government (2008) The Heather and Grass etc. Burning (Wales) Regulations. <https://www.legislation.gov.uk/wsi/2008/1081/made>

Wentworth, J. and Shotter, L. (2019) Climate Change and UK Wildfire, Research Briefing POSTNote, 603. <https://post.parliament.uk/research-briefings/post-pn-0603/>

White, M.P., Alcock, I., Grellier, J., Wheeler B.W., Hartig, T., Warber S.L., Bone, A., Depledge M.H., Fleming L.E. (2019) Spending at least 120 minutes a week in nature is associated with good health and wellbeing. *Sci Rep* 9, 7730. <https://doi.org/10.1038/s41598-019-44097-3>

Whittaker, E. and Gimingham, C. (1962) The Effects of Fire on Regeneration of *Calluna Vulgaris* (L.) Hull. from Seed. *Journal of Ecology*, 50, 815-822. doi:10.2307/2257484

Wilkinson, S.L., Moore, P.A., Flannigan, M.D., Wotton, B.M. and Waddington, J.M. (2018) Did enhanced afforestation cause high severity peat burn in the Fort McMurray Horse River wildfire? *Environmental Research Letters*, 13, 014018.

Winter, G. and Fried, J.S. (2000). Homeowner perspectives on fire hazard, responsibility, and management strategies at the wildland-urban interface. *Society and Natural Resources* 13:33–49.

Worrall, F. and Clay, G.D. (2014) The potential use of heather, *Calluna vulgaris*, as a bioenergy crop. *Biomass and Bioenergy*, 64, 140-151.

Worrall, F., Chapman, P., Holden, J., Evans, C., Artz, R., Smith, P. and Grayson, R. (2011) A review of current evidence on carbon fluxes and greenhouse gas emissions from UK peatland. JNCC Report, No. 442. http://jncc.defra.gov.uk/pdf/jncc442_webFinal.pdf

Wu, M., Knorr, W., Thonicke, K., Schurgers, G., Camia, A. and Arneeth, A. (2015) Sensitivity of burned area in Europe to climate change, atmospheric CO₂ levels, and demography: A comparison of two fire-vegetation models. *JGR Biogeosciences*, 120, 2256-2272.

Xu, J., Morris, P.J., Liu, J. and Holden, J. (2018) Hotspots of peatland-derived potable water use identified by global analysis. *Nature Sustainability*, 1, 246-253.

Yallop, A., Thacker J., Thomas, G., Stephens, M., Clutterbuck, B., Brewer, T. and Sannier, C. (2006) The extent and intensity of management burning in the English uplands. *Journal of Applied Ecology*, 43, 1138-1148.