The causes and prevention of wildfire on heathlands and peatlands in England (NEER014)

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The causes and prevention of wildfire on heathlands and peatlands in England

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Cover photograph

Bicton Common, East Devon Pebblebed Heaths, © David Glaves

Executive summary

Heathlands and peatlands are the most extensive terrestrial semi-natural habitats in England, particularly found in the uplands, but also more locally in lowland areas. They include a range of internationally important vegetation types and associated species and are subject to a range of land management practices and other impacts, including managed burning and wildfires. They provide a range of important provisioning, supporting, regulatory and cultural ecosystem services. As such, they present a number of environmental conservation and land management challenges.

This topic review focused on a series of eight questions on the occurrence, causes, prevention and management of wildfires on open, semi-natural habitats in the UK. These were evaluated against scientific and other evidence that led to the identification of issues for future research.

Context

There are a range of definitions of what constitutes a wildfire used around the world. A UK definition that is widely accepted is “any uncontrolled vegetation fire which requires a decision, or action, regarding suppression” (Scottish Government 2013). There is a consensus that the majority of wildfires worldwide have an anthropogenic origin, though natural wildfires do occur, mostly as a result of lightning.

Changes in seasonal, and rainfall, patterns, linked to climate warming are believed to be significant factors in an increase in the number of wildfires globally. Wildfires are of increasing concern in the UK and their frequency and magnitude are considered likely to increase in response to climate change. Though UK wildfires are not on the scale of those that occur in some other countries, large, severe and sometimes high impact wildfires do occur, especially in drought years, and particularly on heathlands and peatlands. Nevertheless, the majority of wildfires are small (99% of 155,957 incidents over eight years to 2016/17 were less than one ha), though even small wildfires can be disruptive, especially and at the rural-urban interface.

McMorrow *et al*. (2009) noted that “they pose a serious threat to the delivery of ecosystem goods and services, such as carbon retention, erosion prevention, or of provision of habitat for biodiversity, as well as threats to human settlements [and safety] in some situations.” Though occurring less frequently, wildfires can be larger and may be more intense, severe and impactful than managed fires in the UK, though like land management fires, they vary in size and severity, and some may have no greater impact than managed burns. Nevertheless, when they occur, they can pose a threat to heathland and peatland biodiversity and associated ecosystem services.

Scope

The scope of this review is restricted to the occurrence, causes, prevention and management of wildfires on open, semi-natural habitats in the UK, with a particular focus on heathlands and peatlands in England. This reflects Natural England’s role and interest in relation to maintaining and restoring the structure and function of semi-natural habitats, including supporting ecosystem services and related government environment objectives and policies.

Heathland and peatland are extensive in England covering a total of around 560,000 ha (Natural England unpublished data), with an additional 476,000 ha of semi-natural moorland[1], mostly grassland, vegetation. Enclosed semi-natural grasslands (*c*.110,000 ha, Natural England 2008) and some other enclosed semi-natural habitats, including mires and fens, scrub and bracken, on enclosed land on the upland fringe and in the lowlands are not included in the above figures. This suggests that there is over a million hectares of open, semi-natural habitats in England that are

[1] Above the Defra Moorland Line (ADAS 1993).

potentially vulnerable to wildfire. This is particularly the case where 'woody' vegetation occurs, in particular dwarf-shrubs, especially heather, and similar woody species such as western gorse and some scrub species, especially common gorse, and also some grasses, most notably purple moor-grass.

Evidence relating to other habitats and land uses, and overseas has been included where it was felt that aspects of it contributed to understanding of the occurrence, causes, prevention and management of wildfire on open, semi-natural habitats in the UK. Thus, the review does not attempt to comprehensively review the wider worldwide literature on wildfire, and it generally excludes woodlands and forests, cropped land and other improved agricultural land, and urban situations, buildings and infrastructure, though reference is made to them where considered relevant, particularly in relation to wildfire risk and occurrence, and fire behaviour and severity. The review does not consider the impacts of wildfires.

Questions addressed by the review

The following eight questions are the focus of the evidence review:

1. What are the main factors that contribute to the risk and occurrence of wildfire?
2. What are the main wildfire ignition sources?
3. What factors influence fire behaviour and severity?
4. What are the most effective measures for preventing wildfire?
5. What are the characteristics of effective firebreaks?
6. How effective is the Met Office Fire Severity Index in predicting potential fire severity?
7. How effective is 'fire watching' in preventing and reducing the impact of wildfire?
8. What are the most effective measures for reducing the negative impacts of wildfire?

The review summarises and evaluates the evidence base in relation to these review questions. It does not make recommendations on the implications of the findings for policy and/or practice other than in relation to identifying further research needs.

The review process

An initial literature search and a call for evidence from stakeholders produced a list of *c*.2,650 references (excluding duplicates). Filtering on the full reference text reduced this list to 205 references. In addition, there were 81 stakeholder submissions the majority of which were formal papers and reports many of which duplicated references included from the literature search. There were also eight non-analytical submissions involving case reports and opinion pieces, and data sets from eight geographic areas, both of which were treated as individual 'studies' and summarised in appendices. As a result of this process, and following quality assessment and summarising, 174 evaluated studies were used in the review.

Summary of conclusions

The nature and strength of the evidence was reviewed for each question and, from this, evidence statements and the following conclusions were developed. A total of 137 evidence statements were synthesised from the evidence derived from evaluated studies. Of these, all were classed as either strong (42%) or moderate (58%), with none weak or inconsistent. There were clear differences between the questions in the quantity and quality of evidence, and hence number and strength of evidence statements. There was a considerable volume of mostly strong and moderate evidence statements on wildfire risk and occurrence (51 evidence statements), and ignition sources (42), but much more limited, mostly moderate evidence statements on fire behaviour and severity, prevention and reducing impact (with no more than 10 evidence statements for any other questions).

The evidence statements are presented for individual questions in the evidence sections (4–8) and summarised with some interpretation in Section 9 along with overall key findings and conclusions across the questions that are further summarised below. Recommendations for future research and other evidence gathering to address gaps are given in Section 9 and at the end of this summary.

Wildfires occur across the country and on all the main terrestrial habitats but, by area, particularly on heathlands and peatlands. In the uplands, most occur in spring, except in extreme fire years when periodic summer fires may be more frequent. In the lowlands, where the number of fires is much higher, a spring peak is still evident, though fires are more evenly spread over spring and summer, with more in autumn and winter than in the uplands. Although large wildfires are associated with the uplands, they also occur in the lowlands, particularly on heathland. Data from the national Incident Recording System (IRS) for wildfires attended by the Fire and Rescue Services (FRS) indicate that a total of *c*.35,500 ha was affected by wildfire over eight recent years (to 2016/17), though there was much variation between years. The majority of incidents were on open, semi-natural habitats (59% of the total area), especially 'mountain, heath and bog' (48%). Whilst this represents a considerable area over a relatively short period, it is a small proportion of the total area of these habitats in England. Nevertheless, wildfire frequency and magnitude are considered likely to increase in response to climate change.

Natural wildfires due to lightning strikes are rare in the UK and most wildfires are the result of human action, through either arson or accident. Arson is more frequent in the lowlands and in urban and rural-urban fringe areas, while the proportion of accidental fires is higher in the uplands and probably in more rural areas in general. They tend to be associated with public access and recreation, with the majority of accidental wildfires resulting from 'camp' and other fires, especially in the lowlands, though land management burns getting out of control are also a significant cause in the uplands.

Risk and occurrence of wildfire in the UK is associated with hot, dry weather conditions, especially drought (or, particularly in spring, low temperatures and frozen conditions), with particular vegetation characteristics (especially plant functional type, height/structure, (high) fuel load, and (low) moisture content) and human-related accidental ignitions associated with public access, recent or current wildfire and managed burning activity, and arson. These factors also affect fire behaviour, severity and extent, and are also likely to affect impact (though the last is beyond the scope of this review).

The incidence of wildfire, especially large wildfires is episodic, coinciding with dry-spells, especially drought, hot periods and heatwaves, resulting in much variation between years which makes determination of temporal trends difficult, especially as systematic collation of wildfire data nationally is relatively recent, though these data to date show little evidence of clear trends.

More limited evidence was identified on the effectiveness of managing public access and behaviour to reduce wildfire risk and occurrence, especially in the UK, though some partnership and community wildfire initiatives have recently been established that address these issues, including through targeted education. Evidence from one such project in south Wales indicates that proactive and reactive education measures can reduce the incidence of wildfire arson. The Met Office Fire Severity Index (MOFSI) is generally effective in predicting extreme conditions when very severe fires are likely, *should they start*, but there is little evidence on the effectiveness of closure of open access land on wildfire occurrence and severity. The MOFSI does not predict wildfire risk or occurrence, but there is interest in developing a full Fire Danger Rating System (FDRS) for the UK and/or parts of it.

Limited evidence was identified specifically on the effectiveness of other wildfire prevention measures and management to reduce wildfire impacts in the UK, though more evidence and experience in relation to this may be held by practitioners (some of which may have fed into the concurrent Defra review). For at least some of these interventions, for example fuel management, effectiveness may be influenced by factors such as its scale, pattern and frequency, and the use of strategic targeting in relation to risk factors. These factors may also influence wider effects, including on ecosystem services, and result in potential trade-offs between delivery of different objectives and outcomes. Habitat restoration, particularly of peatlands, as well as delivering wider benefits may offer the opportunity to reduce risk and increase resilience to wildfire and other impacts, and potentially address over-dominance of more flammable species, though relatively limited existing evidence was identified on this specifically in relation to wildfire, though it is subject to ongoing study.

Despite differences in the quantity and quality of evidence between the review questions, the review has summarised the available evidence on the occurrence, causes, prevention and management of wildfires in England enabling the identification of evidence gaps and recommendations for future research, as listed below.

Research recommendations

Assessment of the available evidence summarised above highlights evidence gaps, which suggest that the following issues would benefit from further research, monitoring or other investigation:

- Where possible, standardisation of the range of variables recorded and definitions, particularly ignition cause, between IRS and other wildfire recording schemes to enable compatibility of data nationally.
- Improved recording of wildfires not attended by the Fire and Rescue Service, and hence not included in the Home Office's national IRS, using new or existing recording systems, for example those maintained by Natural England and the MOD.
- Extension of the main analyses done so far using the IRS to further explore the occurrence of wildfire in England (and potentially GB/UK) and factors that may influence this and its severity, extent and impact. Specifically, this should include the timing, cause and specific habitat and land use types affected.
- Further exploration, and potentially modelling, of factors associated with the occurrence of wildfires using the IRS and additional data sets held by government and other organisations.
- Wider exploration of the effect of weather events and climate on wildfire occurrence and extent using existing weather, climate and wildfire data.
- A review and extension of the potential use of Earth Observation data to improve wildfire mapping and characterisation, for example, of severity.
- Incorporation of socio-economic aspects in consideration of monitoring and research on wildfire occurrence, severity, extent and impact, and in wildfire prevention and management/control. This should involve engagement with the wildfire community, other stakeholders, land managers and the public.
- Investigation of the relationship between routine managed burning and prescribed burning (and cutting/mowing and other management with a fuel management objective) and wildfire occurrence, extent, and ideally severity and impact. This should consider the potentially beneficial effect of fuel management and how factors such as the scale, pattern frequency and targeting in relation to risk factors affect this, but also the effect of burns escaping control resulting in wildfires and the factors that contribute to and cause such loss of control. The latter may include consideration of indirect effects such as effects of managed/prescribed burns on vegetation composition and water table.
- Investigation, potentially involving modelling, of the most effective burn configuration (patch size, shape, pattern, scale, frequency) and targeting of managed/prescribed burning to manage fuel load to reduce wildfire occurrence, severity, extent and impact. This would need to consider habitat/vegetation type and composition, including types other than just *Calluna*-dominated vegetation.
- Extension of recording and mapping of managed/prescribed burning in England potentially using Earth Observation, particularly in the uplands, in part to contribute towards investigation of the relationship with wildfire occurrence.
- A broader investigation of the effects of wider management interventions, for example, grazing, scrub and bracken management, and drainage, on wildfire occurrence, severity, extent and impact.
- Collation nationally of details on any prosecutions that arise as a result of wildfires (for arson and if possible for breaches of the Heather and Grass Burning Regulations) to allow identification of common issues.

- Extension of research on fire behaviour, fuel moisture dynamics, severity, extent and impact, especially in non-*Calluna*-dominated vegetation, and across habitat transitions, potentially including to forestry/woodland and the urban-fringe, in part to input to future development of a full FDRS.
- In reviewing factors associated with wildfire impact, potential impact should also be considered. This could include assessments of, and inputs to, risk registers and tools developed for wildfire management planning including risk assessment, scoring and mapping and fuel mapping.
- Development of an approach to recording burn severity using a simple on-the-ground method of assessment, potentially for use in wildfire recording schemes and/or Earth Observation.
- Further research on the design and effectiveness of fire and fuel breaks, and fire suppression in open habitats.
- An investigation with the Met Office to consider the technical feasibility of aligning the wildfire component of the Daily Hazard Assessment with the Fire Severity Index and the potential for the DHA to provide a trigger for 'exceptional' conditions instead of MOFSI.
- Further investigation of the development of a UK Fire Danger Rating System, including reviewing implementation, engagement/communication and management, and how best to communicate risk warnings to stakeholders, land managers and the public.
- Exploration of the effectiveness of Wildfire Risk and Fuel Maps and associated guidance, and the role they may have in wildfire prevention and control.
- Investigation of the effectiveness of access closure and restrictions, including Access Management Plans and potentially management restrictions, on wildfire occurrence, severity extent and impact.
- Exploration of the use and effectiveness of fire watching and other Early Warning Systems.
- Research into the influence of sward composition and structure on the occurrence, severity, extent and impact of wildfire.
- Research and monitoring of the effect of peatland and other habitat restoration on wildfire risk, occurrence, severity, extent and impact, and its effect on habitat resilience.
- Investigation into the natural (and historic) fire regime in the UK, its impact on vegetation communities, including an assessment of the extent to which they are fire-adapted.

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1 Introduction

Background

1.1 Heathlands and peatlands are the most extensive terrestrial semi-natural habitats in England, particularly found in the uplands, but also more locally in lowland areas. They include a range of internationally important vegetation types and associated species (Thompson *et al*. 1995 and Natural England 2008) and are subject to a range of land management practices and other impacts, including managed burning and wildfires. It is widely recognised that they provide a range of important provisioning, supporting, regulatory and cultural ecosystem services (Natural England 2009, 2010 and Alonso *et al*. 2012). As such, they present a number of environmental conservation and land management challenges. This is particularly the case in relation to understanding the effects of land management practices, visitor pressure and other impacts, including wildfire, on biodiversity and associated ecosystem services.

Previous Natural England evidence reviews

1.2 In the uplands, these challenges led directly to Natural England's Uplands Evidence Review programme which drew together the best available science to provide sound evidence on the effects of key land management activities on upland biodiversity and ecosystem services. This focused on five key upland land management issues where there had been significant challenges, which were reported on in 2013:

- The impact of tracks on the integrity and hydrological function of blanket peat (Grace *et al*. 2013).
- Restoration of degraded blanket bog (Shepherd *et al*. 2013).
- The effects of managed burning on upland peatland biodiversity, carbon and water (Glaves *et al*. 2013).
- Upland hay meadows: what management regimes maintain the diversity of upland meadow flora and populations of breeding birds? (Pinches *et al*. 2013).
- Impact of moorland grazing and stocking rates (Martin *et al*. 2013).

1.3 This provided a basis for advice and decisions on future management of the uplands. Consideration of other relevant information, such as social and economic factors, landscape and archaeology/historic environment, is an important part of the process of developing our advice, but was not part of the uplands evidence review programme itself (nor the present evidence review).

1.4 Since the above programme was completed, three further Natural England evidence reviews relevant to uplands, and wider heathlands and peatlands, have been completed:

- A desk review of the ecology of heather beetle (Gillingham *et al*. 2015a).
- Desk review of burning and other management options for the control for heather beetle (Gillingham *et al*. 2015b).
- The historic peat record: Implications for the restoration of blanket bog (Gillingham *et al*. 2016).

1.5 The current wildfire evidence review will contribute further to the existing evidence base summarised in the publications listed above (and in other more recent studies and publications), but is a separate project.

The wildfire issue

1.6 There are a range of definitions of what constitutes a wildfire used around the world. A UK definition that is widely accepted is:

> "Any uncontrolled vegetation fire which requires a decision, or action, regarding suppression" (Scottish Government 2013), though this is slightly wider than the scope of this evidence review (see Scope below).

1.7 On a global scale, wildfire occurrence has been reported as increasing in recent decades with associated costs to the environment and society (e.g. International Union of Forest Research Organisations 2018). Changes in seasonal and rainfall patterns, linked to climate warming are believed to be significant factors in an increase in the number of wildfires globally (e.g. Jolly *et al*. 2015), though Doerr & Santín (2016) and Andela *et al*. (2017) report a decline in the global area burned over recent decades. There is a consensus that the majority of wildfires worldwide have an anthropogenic origin (e.g. Balch *et al*. 2016, San-Miguel-Ayanz *et al*. 2018 and Nagy 2018).

1.8 Wildfires are of increasing concern in the UK and their frequency and magnitude are considered likely to increase in response to climate change (Albertson *et al*. 2010 [2+] and Wentworth & Shotter 2019 [3+][2]). Though wildfires in the UK are not on the scale of those that occur in some other countries (Wentworth & Shotter 2019 [3+]), large, severe and sometimes high impact wildfires do occur, especially in drought years, and particularly on heathlands and peatlands (McMorrow *et al*. 2009 [2+] and Forestry Commission England 2019 [2++]). Nevertheless, the majority of wildfires are small (99% of 155,957 incidents 2009/10–2016/17 were less than 1 ha, para. 4.26, Forestry Commission England 2019 [2++]), though even small wildfires can be disruptive, especially at the rural-urban interface.

1.9 McMorrow *et al*. (2009 [2+]) in a comprehensive review of the wildfire issue on UK moorlands[3] and heathlands, noted that "they pose a serious threat to the delivery of ecosystem goods and services, such as carbon retention, erosion prevention, or of provision of habitat for biodiversity, as well as threats to human settlements [and safety] in some situations." Though occurring less frequently, wildfires can be larger and may be more intense, severe and impactful than managed fires in the UK, though like land management fires[4] (Glaves *et al*. 2013), they vary in size and severity, and some may have no greater impact than managed burns (Bullock & Webb 1995, Clay *et al*. 2010, Clay & Worrall 2011, Blundell *et al.* 2013 and Sargent *et al*. 2019). Nevertheless, when they occur, they can pose a threat to biodiversity and associated ecosystem services, particularly of peatlands. Once ignited, in exceptional cases smouldering peatland fires can burn for weeks (e.g. Turetsky *et al*. 2014 [2+]) and expose bare peat, initiate erosion resulting in carbon loss, and be very costly to suppress and restore.

1.10 Wildfires are likely to affect ecosystem response and can damage semi-natural vegetation, habitats and associated fauna. While less severe fires are likely to change community composition and alter vegetation structure by removing the canopy layer (Grau-Andrés *et al*. 2019 [2++]), very severe wildfires can lead to widespread loss of vegetation cover, damage to the seed bank (Maia *et al*. 2012) and exposure of bare peat which may last some time and result in erosion (e.g. Anderson 1997, Maltby *et al*. 1990 and Rothwell *et al*. 2006). Wildfires can also have a range of wider negative environmental effects including on carbon balance, water quality and hydrology (Noble 2019 and Wentworth & Shotter 2019 [3+]), cause

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[2] Evaluated studies are given a categorisation of study type and quality (Tables 2 and 3) in square brackets after the date; non-evaluated references included for context are not. See section 2 for more details on methods.

[3] Unenclosed land in the uplands (Severely Disadvantaged Area) generally above 250 m and above the Defra Moorland Line (ADAS 1993), that comprises a range of open, semi-natural habitats including heathlands, peatlands and grasslands.

[4] Hereafter referred to as management or managed burns or burning, also often called controlled or prescribed burns, though the latter has a more specific meaning on the European continent in relation to burns that address a specified objective, particularly fuel management (para. 5.31) and is used here in the text specifically in relation to such burning.

atmospheric pollution (Kenward *et al*. 2013) and pose a public health risk (Finlay *et al*. 2012, Reisen *et al*. 2015 and Kondo *et al*. 2019). However, as noted earlier, the effect of wildfire is variable and influenced by intensity (energy output from the fire), severity (organic matter consumption) and fire extent, and by other aspects of the fire regime including seasonality and frequency.

1.11 Systematic recording of wildfires by the Fire and Rescue Service (FRS) has been in place in England since 2007 (McMorrow *et al*. 2009 [2+] and Forestry Commission England 2019 [2++]). In the period 2009/10–2016/17, almost 260,000 wildfires were recorded in England. Around half of incidents each year occur in built up areas and gardens. Woodland fires and those on arable land accounted for more 'primary' fires (para. 4.3) than any other land cover types. Around 1% of wildfires each year occur on habitat classified as 'mountain, heath and bog'[5], but in a typical year, these can account for 30–40% of the area burned by wildfire and in fire years (e.g. 2011–2012) can be as much as 80% of the total area (Forestry Commission England 2019 [2++]).

Scope of the review

1.12 The scope of this review is restricted to the occurrence, causes, prevention and management of wildfires on open, semi-natural habitats in the UK, with a particular focus on upland and lowland heathlands and peatlands in England. This reflects Natural England's role and interest in relation to maintaining and restoring the structure and function of semi-natural habitats, including supporting ecosystem services, and related government environment objectives and policies, including climate change mitigation and adaptation, natural capital and net zero (greenhouse gas emissions). It is accepted that there are other wider impacts of wildfires, for example, on improved and cropped agricultural land and on buildings and infrastructure, especially in, and at the interface with urban areas, which also have resource and other implications particularly for the fire and rescue services.

1.13 Literature relating to other habitats and land uses, and overseas has been included where it was felt that aspects of it contributed to understanding of the occurrence, causes, prevention and management of wildfire on open, semi-natural habitats in the UK. Thus, the review does not attempt to comprehensively review the wider worldwide literature on wildfire, and it generally excludes woodlands and forests, cropped land and other improved agricultural land, and urban situations (which are included in data collected nationally on wildfire occurrence in England and the rest of GB and included in this report), buildings and infrastructure, though reference is made to them where considered relevant, particularly in relation to wildfire risk and occurrence, and fire behaviour and severity.

1.14 Though the review includes wildfire prevention and management measures, this is specifically in relation to evidence around their effectiveness, though some of the range of measures and approaches used or potentially available are briefly described in places in the text and appendices.

1.15 The review does not consider the effects or costs of wildfire in general (including in relation to open, semi-natural habitats that are the focus of this review). However, the effects of managed burning were reviewed by Glaves *et al*. (2013)[6] and Harper *et al*. (2018), both of which include some information on wildfires, and specific UK reviews on the effects of wildfires were given by Anderson (1986 and 1997), Tallis (1987), Noble (2019) and, in relation to climate change, Wentworth & Shotter (2019 [3+]). Studies on the effects of individual large and/or severe wildfires include those given by Maltby *et al*. 1990, Gilchrist *et al*. 2004, Davies *et al*. 2013 and 2016 and Sargent *et al*. 2019; also see paras. 1.9–1.10 above).

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[5] 'Mountain, heath and bog' is a land cover class from CEH's Land Cover Map 2007 and 2015 (Morton *et al*. 2011 and Rowland *et al*. 2017) that includes heathlands and peatlands which are the main focus of this review.

[6] Glaves *et al*. (2013) also list previous reviews on the effects of managed burning on upland peatlands (pp. 85–86).

The review questions

1.16 The following eight questions are the focus of the review:

1. What are the main factors that contribute to the risk and occurrence of wildfire?
2. What are the main wildfire ignition sources?
3. What factors influence fire behaviour and severity?
4. What are the most effective measures for preventing wildfire?
5. What are the characteristics of effective firebreaks?
6. How effective is the Met Office Fire Severity Index in predicting potential fire severity?
7. How effective is 'fire watching' in preventing and reducing the impact of wildfire?
8. What are the most effective measures for reducing the negative impacts of wildfire?

1.17 The review summarises and evaluates the evidence base in relation to these review questions. It does not make recommendations on the implications of the findings for policy and/or practice other than in relation to identifying further research needs.

Heathlands, peatlands and other open, semi-natural habitats in England

1.18 Heathland and peatland (bog and fen) habitats are extensive in England covering a total of around 560,000 ha (Natural England unpublished data) made up of around: 236,000 ha of upland heathland and 70,000 ha of lowland heathland[7]; 230,000 ha of blanket bog and 17,400 ha of lowland raised bog; and 5–10,000 ha of lowland, mostly purple moor-grass *Molinia caerulea*-dominated, mires and fens. The majority of each of these habitats is in unfavourable condition as a result of a range of past and current impacts.

1.19 Other open, semi-natural habitats potentially affected by wildfire include some frequently associated with upland and lowland heathlands and peatlands, such as scrub, particularly common gorse *Ulex europaeus* and to a lesser extent broom *Cytisus scoparius*, bracken *Pteridium aquilinum*, especially its litter, and a range of other typically graminoid-dominated semi-natural grasslands, fen-meadows, and other mires and fens. Many of these occur above the Defra 'Moorland Line' which maps generally unenclosed, semi-natural upland vegetation (ADAS 1993) which covers a total area of 799,000 ha indicating an additional 476,000 ha of moorland vegetation on top of the area of blanket bog and upland heathland.

1.20 Enclosed semi-natural grasslands (*c*.110,000 ha, Natural England 2008) and some other semi-natural habitats, including mires and fens, scrub and bracken, on enclosed land on the upland fringe and in the lowlands are not included in the above figures. This suggests that there is over a million hectares of open, semi-natural habitats in England that are potentially vulnerable to wildfire. This is particularly the case where 'woody' vegetation occurs, in particular ericaceous dwarf-shrubs, especially heather *Calluna vulgaris*[8], and similar woody species such as western gorse *Ulex gallii*, and some scrub species, especially *Ulex europaeus*, but also graminoids, particularly when deciduous and/or dry, most notably purple moor-grass *Molinia caerulea*[9].

Definitions and species names

1.21 Definitions of wildfire and other terms included in the text and used more widely are given in a glossary (Appendix 11). Both English and scientific names of species are given on their first

[7] Wet heath, usually on shallow peat soils, is generally regarded as a peatland habitat, but here (as with the UK BAP priority habitats) is included in upland and lowland heathland and not with blanket or raised bog, or fen peatland habitats.

[8] Hereafter referred to as *Calluna*.

[9] Hereafter referred to as *Molinia*.

mention in the text and subsequently scientific names are given for plants and English names where commonly used for some plant groups and for animals.

2 Methods

2.1 This section briefly describes how the review was undertaken, broadly following the approach described in more detail in *Natural England Evidence Reviews: guidance on the development process and methods* (Stone 2013). Some differences in detail from the guidance were adopted as described in the following sub-sections. This included incorporating aspects of the Rapid Evidence Assessment method for evidence reviews (Collins *et al*. 2015).

2.2 Aspects of a mixed-methods approach were used, particularly in relation to the collation and assessment of evidence based on a combination of: (1) the normal Natural England systematic evidence review approach (Stone 2013); and (2) the involvement of key stakeholders, partners, academics and other individuals through consultation on the basis of draft questions developed for the review by Natural England (in consultation with Julia McMorrow, University of Manchester), including an open call for submission of practitioner as well as scientific evidence, including from land owner and manager representative bodies.

2.3 For (1) above, the systematic literature searches and screening were followed by the normal Natural England evidence review approach to study categorisation, assessment and synthesis, leading to the development of evidence statements categorised by strength of evidence. For evidence submitted under (2) above, scientific and technical papers and reports, and other formal documents were screened and then treated in the same way as with (1). A number of data sets on wildfire occurrence were submitted for specific geographical areas and were evaluated together with unpublished Natural England data and presented together in Appendix 2. A smaller number of other non-analytical submissions involving case reports and opinion pieces were harder to evaluate, but were also classed by type (types 3 or 4, Table 2) and quality, in some cases summarised grouped together and presented in Appendices.

2.4 A concurrent, wider Defra review of *Wildfire and the management of upland peatland habitats in England* (Defra in press.)[10] was broader in scope in reviewing the effects of current land management policies and tools available for the reduction of wildfire risk, examining the evidence base to ascertain where changes to policies and approaches might be appropriate, and whether further research and evidence is needed, and identifying what needs to change to ensure that future land management policies help to minimise the risks from wildfire in the uplands. A Parliamentary Office of Science and Technology (POST) review note on *Climate change and UK wildfire* (Wentworth & Shotter 2019 [3+]) was also produced whilst the current review was underway. Both were informed by the evidence base presented in this report.

General principles

2.5 The review process systematically identified all available studies providing evidence for the specific questions posed. A long preliminary list of documents was screened and sifted, to ensure that those included met defined criteria ('inclusion criteria') and/or did not meet others ('exclusion criteria').

2.6 Normally the 'PICO' (Population, Intervention, Comparison, Outcome) framework (e.g. James *et al*. 2016) is used in Natural England evidence reviews to provide a structured approach to formulating review questions and framing the over-arching search strategy and sift criteria (Stone 2013). It derives from medical reviews and works well when applied to management (c.f. medical) interventions on habitat or species populations. However, as this review is not about the effects of one clear intervention on a population, but rather the multiple causes of,

[10] Also see Defra wildfire and upland peatlands stakeholder workshop report, Thorp 2018, available at: https://www.northumberland.gov.uk/NorthumberlandCountyCouncil/media/Fire-and-Rescue/Final-Report-from-Wildfire-Workshop-on-8th-February-2019-in-Nottingham.pdf.

and prevention and management measures to control, wildfires, the PICO approach was not formally used. Nevertheless, the population is heathlands, peatlands and other open, semi-natural habitats in England and the causes of wildfire could perhaps be viewed as a range of different natural, accidental or deliberate ‘interventions’, and prevention and management measures similarly could be considered a range of different (rather than a single) intervention. Thus, in this review, habitats, wildfire causes, and types of prevention and management interventions were used as categories for the development of review questions and selection of search terms and sift criteria.

2.7 The review provides a narrative overview of the evidence from included studies, with evidence statements providing a synthesis for each question.

Evidence search

2.8 Literature searches were conducted using the terms listed below for the systematic review component (para. 2.2 above). References were downloaded or manually added, if necessary, into a reference manager database (EndNoteWeb). Duplicate references were removed.

Search terms and strategy

2.9 Potential search terms were identified to cover habitats, wildfire causes, prevention and management interventions in search plans for each of the eight review questions. The following search terms were used in Boolean searches:

> arson, burn severity, burned area, campaign, climate condition, climate, control, damage, drought, ecological resistance, education, effective, effectiveness, efficient, fire cause, fire frequency, fire history, fire intensity, fire size, fire weather index (FWI), firebreaks, fire-watcher networks, forest management, fuel continuity, fuel load, fuel reduction, heath, heathland, humidity, management burning, management, Met Office Fire Severity Index, occurrence, partnership work (with fire services), peat, peatland, prevailing weather, prevent, productivity, public access, radio, range, rangeland fire, rangeland, recreation, recreational access, reduce, reduction, response time, restrict access, rewetting, risk, rotational burning, school holidays, season, severity, SMSs, temperature, TV, uncontrolled fire, vegetation condition, weather condition, wild fires, wild land fire, wildfire hazard management, wildfire, wildland fire, wind, and (wild)fire.

The Web of Science (from 1990) and SCOPUS reference database were searched.

2.10 It became apparent from initial search results that there was a lot of overlap of references between review questions and also that some wider wildfire or wildfire-related studies included aspects that were potentially relevant to the UK, especially regarding habitats, prevention and management interventions and fire behaviour. As a result, further separate literature searches were conducted using the following search terms:

> Bush fires, fires, forestry, fuel load, grassland, heath, heathland, ignition, moorland, peatland, range, vegetation, wildfire, wild fire, wildland, and woodland.

The resultant references were then combined with those from the earlier searches relating to the individual questions (para. 2.9).

2.11 Relevant references were also identified through online searches and contact with a number of external international and national experts and organisations (see acknowledgements), including four external experts who peer reviewed two earlier drafts of the report, and from scrutinising other relevant recent reviews: Gallani (2002 [3-]), McMorrow *et al*. (2009 [2+]), Glaves *et al*. (2013), Shepherd *et al*. (2013), Harper *et al*. (2018) and Wentworth & Shotter (2019 [3+]).

Evidence submitted

2.12 The open call for evidence resulted in about 80 submissions from stakeholders and individuals, the majority of which were formal papers and reports which were treated in the same way as references coming from the literature search, though there were also eight[11] non-analytical submissions involving case reports and opinion pieces listed and summarised in Appendix 4.

2.13 In addition, data on wildfire occurrence were submitted for seven specific geographical areas by: Calderdale Fire Operations Group, Dorset County Council, Exmoor National Park, Lancashire Fire and Rescue Service, Moors for the Future Partnership, Peak District National Park and Pennine Prospects (South Pennines). This is summarised, along with a previously unpublished Natural England wildfire data set, in Appendix 2.

Selection of references for inclusion

2.14 The number of references considered and included in each part of the review is given in Table 1. The search strategy resulted in 7,240 titles (including duplicates). These were screened by title and abstract for relevance. Sifting was done by one reviewer and checked by a second and differences of opinion discussed and agreed. A total of 205 references were accepted for quality assessment plus 81 submissions (many duplicating references already accepted), of which 174 evaluated references were used in the development of evidence statements.

Table 1. The number of references included in each stage of the review.

Review stage	Number of references
References captured using search terms in all sources (including duplicates)	7,240
References remaining after de-duplication and title and abstract filters	2,633
References remaining after full text filter	205
References submitted by stakeholders and others	81[1]
Evaluated references used in the development of evidence statements[2]	174[3,4]

[1] Many duplicating references remaining after full text filter.
[2] Not including non-evaluated references included to provide context and aid interpretation.
[3] Natural England/submitted English wildfire data evaluated together in Appendix 2 counted as one reference.
[4] Practitioner evidence/opinion evaluated together in Appendix 4 counted as one reference.

Study type and quality appraisal

2.15 Each study was categorised by study type (categorised as type 1–4, Table 2) and graded for quality against criteria appropriate for the study type (including area/population, method of allocation to intervention or comparison, outcomes and analyses for quantitative studies and theoretical approach, study design, data collection, trustworthiness, analyses and ethics for qualitative studies) using a code: [‘++’], [‘+’] or [‘-’] (Table 3), based on the extent to which potential sources of bias had been minimised. The assessment of study quality was streamlined; in particular, the full assessment forms recommended by Stone (2013) were not completed. This assessment was in relation to the overarching wildfire review topic and individual questions, rather than necessarily for the reference as a whole that sometimes also addressed other issues. As mentioned earlier (para. 2.3), technical papers, reports and other documents submitted to the review were assessed in the same way. A smaller number of

[11] One submission listed in Appendix 4, a longer-term case study report by Martin (2018 [3+]), was treated as a technical report and included with other technical paper and report submissions and the references coming from the literature search for evaluation.

other non-analytical submissions involving case reports and opinion pieces were harder to evaluate, but were also classed by type (types 3 or 4, Table 2) and quality, in some cases categorised and summarised grouped together and presented in appendices.

Table 2. Categorisation of study types.

Rating	Definition
1	Meta-analyses, systematic reviews of, or individual Randomised Control Trials (RCT).
2	Systematic reviews of, or individual, non-randomised control trials, case-control trials, cohort studies, controlled before-and-after (CBA) studies, interrupted time series (ITS) studies, correlation studies, modelling, site comparisons and national or regional (and some local) data sets, statistics and surveys.
3	Non-analytical studies, for example, case reports and case series studies, and traditional, non-systematic literature reviews.
4	Expert opinion and formal consensus.

Table 3. Categorisation of study quality.

Rating	Definition
++	All or most of the methodological criteria were fulfilled. Where they had not been fulfilled, the conclusions are thought very unlikely to alter (low risk of bias).
+	Some of the criteria were fulfilled. Those criteria that had not been fulfilled or not adequately described are thought unlikely to alter the conclusions (risk of bias).
-	Few or no criteria were fulfilled. The conclusions of the study are thought likely or very likely to alter (high risk of bias).

Study categorisation

2.16 This section presents a summary of the type, quality and location of the 174 evaluated studies included in the topic review. Similar information for individual studies is given in Appendix 1.

Table 4. Categorisation of type and quality of evaluated studies included in the review.

Study type	Study quality			Total
	++	+	-	
1	3	1	0	4
2	50	79	4	133
3	1	21	12	34
4	0	1	2	3
Total	54	102	18	174

2.17 Only four studies (2%) were categorised as type 1, with the majority, 133 (76%) as type 2, 34 (20%) as type 3 and three (2%) as type 4 (Table 4). In terms of quality, 54 (31%) were classed as [++], 102 (59%) as [+] and 18 (10%) as [-].

Study sub-types

2.18 The findings from the 173 evaluated studies fed into in the development of evidence statements which are described in Sections 4–8 of the report, with more information on the individual studies given in Appendix 1. They comprise the following study sub-types (based on a single main type for each study), with the majority primary studies (75%):

- 73 correlation/modelling studies/observations;
- 43 reviews;
- 36 site comparison/modelling studies;
- 10 experimental studies;
- 6 ignition testing/modelling studies;
- 3 data sets/analyses;
- 1 monitoring study;
- 1 economic study; and
- 1 practitioner opinion/experience submission.

Country of studies

2.19 The majority of evaluated studies were undertaken in the UK, involving 47 primary studies and 30 reviews, followed by North America (37, 11), the rest of Europe (30, 3), Australia (16, 9) and Africa (6, 1), with no others no more than two in total (Table 5). Overall within the UK, most were from England (15 primary studies and 7 reviews) and Scotland (17, 1), with only two (primary) studies from Wales and none from Northern Ireland (in these figures UK cross-nation studies were included in each nation they occurred in).

Table 5. The number of evaluated studies by continent/country of origin.

Continent/country of origin	Number of primary studies	Number of reviews	Total
UK	47	30	77
North America	37	11	48
Europe (apart from UK)	30	3	33
Australia	16	9	25
Africa	6	1	7
China	2	0	2
South America	2	0	2
Worldwide	0	2	2
Japan	1	0	1

Assessing applicability

2.20 Each study was assessed on its external validity: that is, whether or not it was directly or indirectly applicable to the occurrence, causes, prevention and management of wildfires in the UK, particularly affecting the target habitats and landscapes: upland and lowland heathlands and peatlands, and other open, semi-natural habitats, especially in England. This assessment took into account whether the study was conducted in the UK, how relevant it was to the English open, semi-natural habitat resource as a whole and any barriers identified by studies or the review team. This was taken into account in the categorisation of the study and the strength of evidence of evidence statements to which it contributed.

Synthesis

2.21 The topic review was restricted to a narrative overview of studies that met the inclusion criteria and contained sufficient information for quality assessment and contributed to the development of evidence statements. The studies were examined in relation to the causes, prevention and management of wildfires on heathlands, peatlands and other open, semi-natural habitats in England as identified by the eight questions (para. 1.16). The evidence statements were developed using:

- The best available evidence of the causes, prevention and management of wildfires, including the study type. With some exceptions where reviews contributed (which are specifically noted in the text), this was from primary and/or modelling studies.
- The quality and quantity of supporting evidence and its applicability to the areas/populations and settings in question.
- The consistency and direction of the evidence.

2.22 Based on these factors, the strength of the evidence on particular aspects (where there was clear evidence of an effect) was classed as strong, moderate, weak, or inconsistent (where findings, e.g. direction or trends, differed between studies). This is partly a subjective judgment taking into account the above factors, though the following criteria (modified from the Upland Evidence Review guidance (Stone 2013, para. 1.2) were used as guidance:

- **Strong**: a number of studies (typically at least four) showing consistent findings or trends or one or two high quality or national, regional or sometimes local, representative studies or data sets (generally including Office for National Statistics recognised data) [1++, 1+ or 2++].
- **Moderate**: a smaller number of studies (typically at least two) of which at least one was classed as a minimum of [2+].
- **Weak**: one study or a low number of generally lower quality studies, usually including some or most with quality classed as minus [-].

3 Introduction to the Evidence Review question sections and framework

Conceptual framework and relationship between questions

3.1 The relationship between questions was investigated by placing the individual questions in a modified version of Prestemon *et al*'s (2013 [3+]) wider conceptual model of wildfire ignitions and preventions (Figure 1). This model was used as it covered the range of questions previously developed and consulted on in the initial stages of the current review in terms of biophysical and social drivers (that affect risk), ignition sources, fire behaviour, and prevention and management. It was used simply to provide a framework a help identify the links, overlaps and scope of the individual questions and also for the Summary, interpretation and conclusions section (9). Where possible, overlap and hence the possibility of duplication between questions has been reduced by dealing with such overlaps under what was considered the most appropriate question (as explained in the introduction to each question) and through cross-referencing.

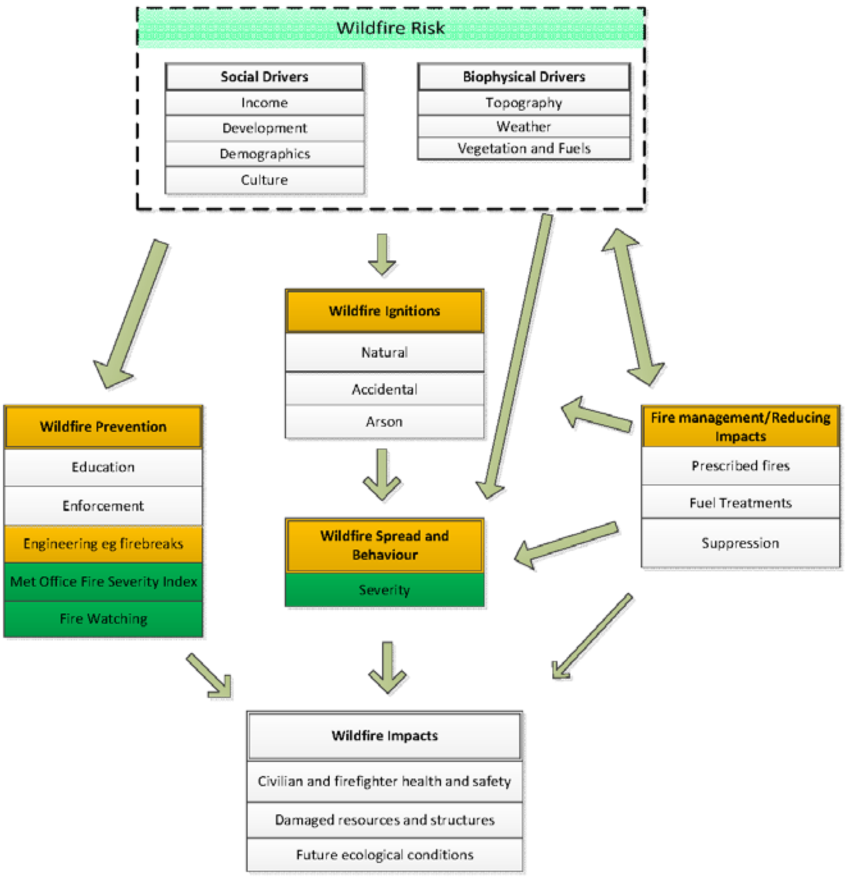

Figure 1. The conceptual framework used to identify the relationship between the review questions (highlighted in orange, or green when additional to Prestemon *et al*'s (2013 [3+]) conceptual model which the figure is adapted from) and wider aspects of wildfire causes, prevention and management.

3.2 As noted earlier, there is a degree of overlap between some of the review questions. In particular, several relate to specific prevention measures (firebreaks, Met Office Fire Severity Index and fire watching) which is also considered as a separate wider general question. Thus, for clarity they have been presented together in a single section (7) of the report on wildfire prevention. There are also clear links between factors contributing to wildfire risk (including fuel biomass, fire weather and low moisture content) and ignition, and also between ignition and fire behaviour (including initial spread) and severity.

3.3 Reflecting the overlap and links between many of the review questions, many of the studies reviewed were relevant to multiple questions. Hence, information about the characteristics of the studies and their applicability is summarised across the questions in relation to the causes, prevention and management of wildfire in open, semi-natural habitats in the UK, particularly heathlands and peatlands in England (para. 1.2).

Summaries of the evidence

3.4 The evidence relevant to the eight questions and key aspects of each (under sub-headings) is summarised in the following Sections (4–8) in the form of evidence statements. These were developed initially from summaries of findings across evaluated studies to identify common themes. This was followed by synthesis of statements mostly across multiple studies, which indicate the strength of the evidence based on characteristics of the individual studies (type/quality) that directly support them and the consistency of the findings (paras. 2.21–2.22). The development of evidence statements involved assessment of all evaluated studies that were considered relevant, even though not all are listed in support of individual statements. However, as they contributed to the process, brief information about all evaluated studies is presented in Appendix 1.

3.5 In some cases where there were numerous studies relating to a similar aspect, evidence statements were developed at two levels: a broad, initial overall summary statement across all relevant studies and more detailed supporting summaries of individual, or groups of related, studies. The former appear as numbered paragraphs and the latter as bullets identified by letters (to enable cross-referencing).

3.6 Within evidence statements, the studies that contribute are listed in order of study type and quality, date, and author(s) (alphabetic). Under main or sub-headings, the evidence statements are arranged from the more general to more specific, with UK studies and those covering heathlands, peatlands and other open, semi-natural habitats presented first. Non-UK studies and statements are indicated by giving the country or other geographic region in bold.

3.7 In addition to the evidence statements themselves, in places, particularly in the introduction to the section or introductory text under sub-headings and in the Summary, interpretation and conclusions (Section 9), the narrative text also includes some supporting contextual information to aid understanding and interpretation of the evidence in relation to the specific question and the overarching topic of the causes, prevention and management of wildfire on heathlands, peatlands and other open habitats in England.

3.8 Evidence gaps and research recommendations are identified for each question after the summary of evidence and are brought together in the Summary, interpretation and conclusions.

4 Wildfire risk and occurrence

4.1 The full text of question 1 is:

What are the main factors that contribute to the risk and occurrence of wildfire?

Introduction

4.2 This question has been interpreted to refer to the social, and especially biophysical, drivers (Figure 1) that individually or in combination pose a risk of ignition and a hence of a wildfire occurring. Thus, they are here taken to include the conditions necessary for ignition (and initial spread) to occur, though direct sources of ignition itself are considered in Section 5. There is, however, some overlap between risk, ignition and severity (Section 6) as, in particular, biophysical drivers such as fuel load and structure, and fuel moisture conditions, affect not only ignition but wildfire behaviour post-ignition, including spread and intensity, and fire severity (para. 6.2). Risk may have different meanings, but is used here in relation an uncontrolled fire occurring that requires a decision, or action, regarding suppression (para. 1.16), not just large, severe and damaging or impactful fires.

4.3 Evidence on wildfire occurrence, especially in the UK, and how this relates to risk is also included under this question as it provides information on the likely importance of different biophysical, and to some extent social, drivers. Of particular relevance to this is the Forestry Commission England's (FCE) analysis of recent wildfires attended by the Fire and Rescue Service (FRS) and recorded in the Home Office's UK Incident Recording System (IRS) database[12] over eight years between 2009/10 and 2016/17 (Forestry Commission England 2019 [2++]). This provides data on three categories of wildfire: 'all wildfires' attended by FRS (258,867 incidents covering 36,916 ha), National Operational Guidance Programme (NOGP) fires[13] (7,141 incidents covering 35,470 ha) and potentially serious 'primary fires' that harm people or cause damage to property[14] (*c*.15,000 incidents). The majority of wildfires on open, semi-natural habitats, especially heathlands and peatlands, which are the focus of this review are likely to be NOGP fires ('medium', >1 ha to 49 ha or greater based on the UK Vegetation Fire Standard (UKVFS, Gazzard 2009) with a proportion also 'primary fires', though all these categories also include a proportion of fires in built-up areas and gardens, and vegetation fires on non-semi-natural habitats, such as 'improved' grassland and cropped agricultural land. The FCE report provides information on wildfire occurrence by year, land cover types, including 'mountain, moor and heath' which is likely to include most heathland and peatland, and designated sites and areas, but not on causes or date/month/season.

4.4 The Forestry Commission also submitted an additional, new analyses of these IRS (2009/10–2016/17) national data: (1) giving the density of wildfire incidents by English regions taking into account the area of each region (Forestry Commission in litt. 2019a [2++]) and (2) for a sub-set comprising 'upland' areas (above 250 m *and* in the Defra Moorland Line, ADAS 1993) to the review (Forestry Commission in litt. 2019b [2++] and Appendix 2). Upland was defined as 'mountain, heath and bog', and 'semi-natural grassland' land cover categories (Rowland *et al*. 2017) above 250 m and in the Defra Moorland Line, i.e. 'moorland'. This included splits by

[12] An electronic database introduced in July 2007 by the Department for Communities and Local Government, which transferred to the Home Office along with responsibility for fire and rescue policy in January 2016.

[13] NOGP fires meeting one or more of the following criteria: ≥1 ha; with a sustained flame length >1.5 m; requires a committed resource of four or more FRS appliances; resources committed for ≥6 hours; or presents a serious threat to life, environment, property and infrastructure.

[14] 'Primary fires' meeting one or more of the following criteria: fire in a (non-derelict) building, vehicle or (some) outdoor structures; involving fatalities or casualties or rescues; or attended by five or more pumping appliances.

UKVFS fire size categories, land cover types, National Parks and month (the last not included in the earlier national analysis, Forestry Commission England 2019 [2++]).

4.5 A proportion of wildfires, including out of control managed burns, are brought under control usually by land managers or go out without the need of intervention from the FRS. Hence, they are not included in the IRS database, though some are probably included in incomplete data on wildfire occurrence compiled by Natural England (para. 4.6 and included in some of the data derived from it below). The number of such fires is unknown. They might also differ in some characteristics from IRS fires, for example, in terms of likely causes and types of land affected. Thus, there is a need to improve recording of these fires through the Natural England wildfire database and/or other wildfire data recording.

4.6 Similar, but known to be incomplete, previously unpublished data on the occurrence of wildfires affecting open, semi-natural habitats, especially designated (SSSI and Natura) sites and agri-environment agreements, known by or reported to Natural England have been collated nationally by Natural England since 2011. This, along with other recent data sets submitted to this review covering a similar period (though some back to 2002) and a range of English regional and local geographic areas (Dorset, Exmoor, Peak District, South Pennines and Lancashire), were included in the review and are presented in more detail in Appendix 2 ([2+]). In interpreting information from this combined data set, it should be borne in mind that though the Natural England data cover England, the submitted data are for particular areas and hence may not be representative of England as a whole.

4.7 Other similar large and/or relatively long-running data sets on wildfire occurrence contributing mainly to this, but also some other, sections include:

a. de Jong *et al*. (2011 [2++]) involving 2,921 FRS recorded ‘NOGP-type’[15] wildfires covering an area of 51,609 ha in *GB* based on an analysis of incidents in the IRS database over just three years between January 2010 and December 2012.

b. Jollands *et al*. (2011 [2+]) involving 55,331 ‘grassfires’ and nearly 527 forest fires in the Forestry Commission Wales District of Coed y Cymoedd in south *Wales* between 2000 and 2008.

c. Luxmoore (2018 [2+]) involving a *Scotland*-wide analysis of FRS records of 233 ‘primary wildfires’ over five years between 2009/10 and 2014/15.

d. McMorrow *et al*. (2009 [2+]) and Moors for the Future (2009 [2+]) involving over 400 fires recorded by Peak District National Park rangers, *England*, over a long, unbroken 33-year period up to 2008 (including 352 between 1976 and 2004, McMorrow *et al*. 2009 [2+]).

4.8 The above and other data sets and evidence on wildfire occurrence mostly provide data on recorded or reported wildfires across all habitats, though some relate occurrence to broad habitat types/groups which is summarised in para. 4.22. Only limited information was identified on wildfire occurrence by more narrowly defined individual habitats, e.g., UK Biodiversity Action Plan (BAP) Priority Habitats (Maddock 2008), or vegetation types, e.g. blanket bog, though some information on these are included in the Natural England data set.

4.9 Biophysical drivers were classed by Prestemon *et al*. (2013 [3+]) under three general categories: topography, weather, and vegetation and fuels, with the last two, in particular, being the main focus of this section.

4.10 Social drivers were classed by Prestemon *et al*. (2013 [3+]) under four general categories: income, development, demographics and culture, and considered to be largely immutable to actions that land management agencies or managers can take (in the USA), even though they

[15] Based on three of the NOGP criteria: burned area >1 ha; >6 hours elapsed between reporting and extinction; and >3 firefighting appliances in attendance (de Jong *et al*. 2016 [2++]).

may be influenced by broader-scale national, regional or local policies. Such human-related factors and ignition sources are here mainly considered in the next section (5) on ignition.

Summary of evidence on wildfire risk and occurrence

General wildfire occurrence in the UK

4.11 There is strong evidence that risk and occurrence of wildfire in the UK is associated with three main factors: particular weather conditions; vegetation characteristics, especially of dominant plant species, which contribute to wildfire hazard; and human-related factors (Davies *et al*. 2010 [2++], de Jong *et al*. 2016 [2++], Grau-Andrés *et al*. 2018 [2++], Albertson *et al*. 2009 [2+], Davies 2005 [2+], Davies & Legg 2011 [2+], Jollands *et al*. 2011 [2+], Davies & Legg 2016 [2+]), Tantram *et al*. 1999 [2-], Aylen *et al.* 2007 [3+] and Legg & Davies 2009 [3+]). Weather associated with wildfire, particularly large, severe wildfires, typically involves dry, warm conditions, especially severe and/or prolonged drought, or, particularly in spring, low temperatures and frozen conditions. Vegetation and dominant plant species' (particularly *Calluna* and *Molinia*) characteristics affecting wildfire occurrence include functional type, autecology, phenology, age/growth stage and height/structure, fuel load and fuel structure, and moisture content, which together contribute to wildfire hazard. Human-related factors include accidental ignition associated with public access, recent or current wildfire and managed burning activity, and deliberate arson[16].

4.12 There is moderate evidence that physical environment characteristics, for example, geographic location, altitude, topography including slope, aspect and soil type, and remoteness, may contribute to risk or may influence some of the other main risk factors listed above (McMorrow *et al*. 2009 [2+] and Davies *et al*. 2008 [3+]).

4.13 Individual factors relating to the occurrence of wildfires (including those above), mostly in the UK, are considered further in the following sub-sections, though specific human-related factors are dealt with mainly in the next section (5) on ignition sources (see especially para. 5.8–5.11).

Geographic distribution in the UK

4.14 There is strong evidence that wildfires occur widely in GB and across all English regions, but more frequently in some, though the type[17], frequency, and extent show regional patterns of variation (de Jong *et al*. 2016 [2++], Forestry Commission England 2019 [2++], Davies & Legg 2016 [2+], Luxmoore 2018 [2+] and Appendix 2, Natural England data 2012–18) [2+]). This includes strong evidence from the following national and regional data sets and studies:

a. Strong evidence that 'NOGP-type' wildfires occur in all areas of *GB* based on an analysis of 2,921 FRS recorded incidents in the IRS database over three years (2010–12, para. 4.3a), but most frequently in south Wales (also see (h) below which supports this), south-east England and the southern Pennines (de Jong *et al*. 2016 [2++]).

b. Strong evidence from an analysis of recent wildfires attended by the FRS in *England* recorded in the IRS database over eight years (2009/10–2016/17, para 4.3), that incidents ('all wildfires') occur across all English regions: with most in the North West (40,114 incidents, 16%); followed by Yorkshire and the Humber (35,109, 14%); West Midlands (33,516, 13%); South East (32,673, 13%); Eastern (27,098, 11%); London (25,456, 10%); North East (25,316, 10%); East Midlands (21,761, 8%); with least in the South West (17,775, 7%) (Figure 2 and Forestry Commission England 2019 [2++]).

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[16] Arson is defined in this report as the deliberate setting of a fire by a person who is not the landowner and who is not operating under the guidance of the landowner (irrespective of whether a prosecution has been made or not).
[17] Wildfire classes: 'all wildfires', NOGP wildfires, 'primary wildfires' (para. 4.3) and wildfires on open, semi-natural habitats (NE data, para. 4.6).

c. However, the land area of *English* regions varies with London, in particular, covering a much smaller area than all eight other regions. The Forestry Commission also submitted an additional analysis of the IRS (2009/10–2016/17) wildfire incidents taking account of each region's size (Forestry Commission 2019a [2++]). This provides strong evidence that the region with the greatest *density* of wildfire incidents is in fact London, with 16 incidents/km^2, four times the overall average for England of 3.6 incidents/km^2. The region with the second greatest density of wildfire incidents is the North East (2.9 incidents/km^2), followed in descending order by the North West (2.8 incidents/km^2); West Midlands (2.6 incidents per km$^{2)}$; Yorkshire and the Humber (2.3 incidents per km^2); South East (1.7 incidents per km^2); then Eastern and the East Midlands (each with 1.4 incidents/km^2); and the South West with the lowest density (0.7 incidents/km^2).

d. Strong evidence from the same analysis of recent *English* ('all') wildfires recorded in the IRS database over eight years (para. 4.14b above), that the pattern between regions differs for area burned: with the largest area also in the North West (18,879 ha, 50%); but then followed by the South West (6,962 ha, 19%); Yorkshire and the Humber (5,713 ha, 15%); South East (2,704 ha, 7%); Eastern (1,288 ha, 3%); and with <1,000 ha in the East Midlands (917 ha, 2%), West Midlands (539 ha, 1%), London (402 ha, 1%) and North East (322 ha, 1%) regions (Figure 2 and Forestry Commission England 2019 [2++]).

e. Taking into account the land area of the *English* regions, there is strong evidence that the region with the greatest area burnt *per area* of the region in wildfire incidents is still the North West, with an overall average of 1.3 ha/km^2 over the eight year (2009/10–2016/17) IRS data set period (Forestry Commission 2019a [2++]). This is about four times the overall average for England as a whole which is 0.3 ha/km^2 of regional land area. The region with the second greatest area burnt allowing for the size of the region is Yorkshire and the Humber (0.4 ha/km^2); followed by the South West (0.3 ha/km^2) which had the lowest density of incidents (para. 4.14c); then in descending order by London, the South East, Eastern, East Midlands, West Midlands and North East.

f. Strong evidence from 127 recent *English* wildfire incidents collated by Natural England over seven years (2012–2018, para. 4.6 and Appendix 2 [2+]) that wildfires on open, semi-natural habitats occur in both lowland (56%) and upland (44%) areas. In the wider England data set including submissions to this review, a higher percentage occurred in the lowlands (85%, para. 4.15c), and in all regions, with most in Yorkshire and the Humber and South East (both 25%), followed by South West (21%), North West (13%), North East (7%), West Midlands (4%), East Midlands (4%) and Eastern (2%) regions (none were reported in London) (Appendix 2 [2+]).

g. Strong evidence from a *Scotland*-wide analysis of FRS records of 233 'primary wildfires' over five years (2009/10–2014/15, para. 4.7c) of a concentration in Highland region (mean 12 per year), though it is much larger than other regions so it would be expected to have more, with fewer than 20 in total in all other regions (Luxmoore 2018 [2+]). This is supported by an analysis of 4,343 FRS 'all wildfire' incidents between 2003 and 2007 which also showed most in Highlands, then Lothian, Grampian and least in Dumfries, former Fire Brigade Regions (Davies & Legg 2016 [2+]).

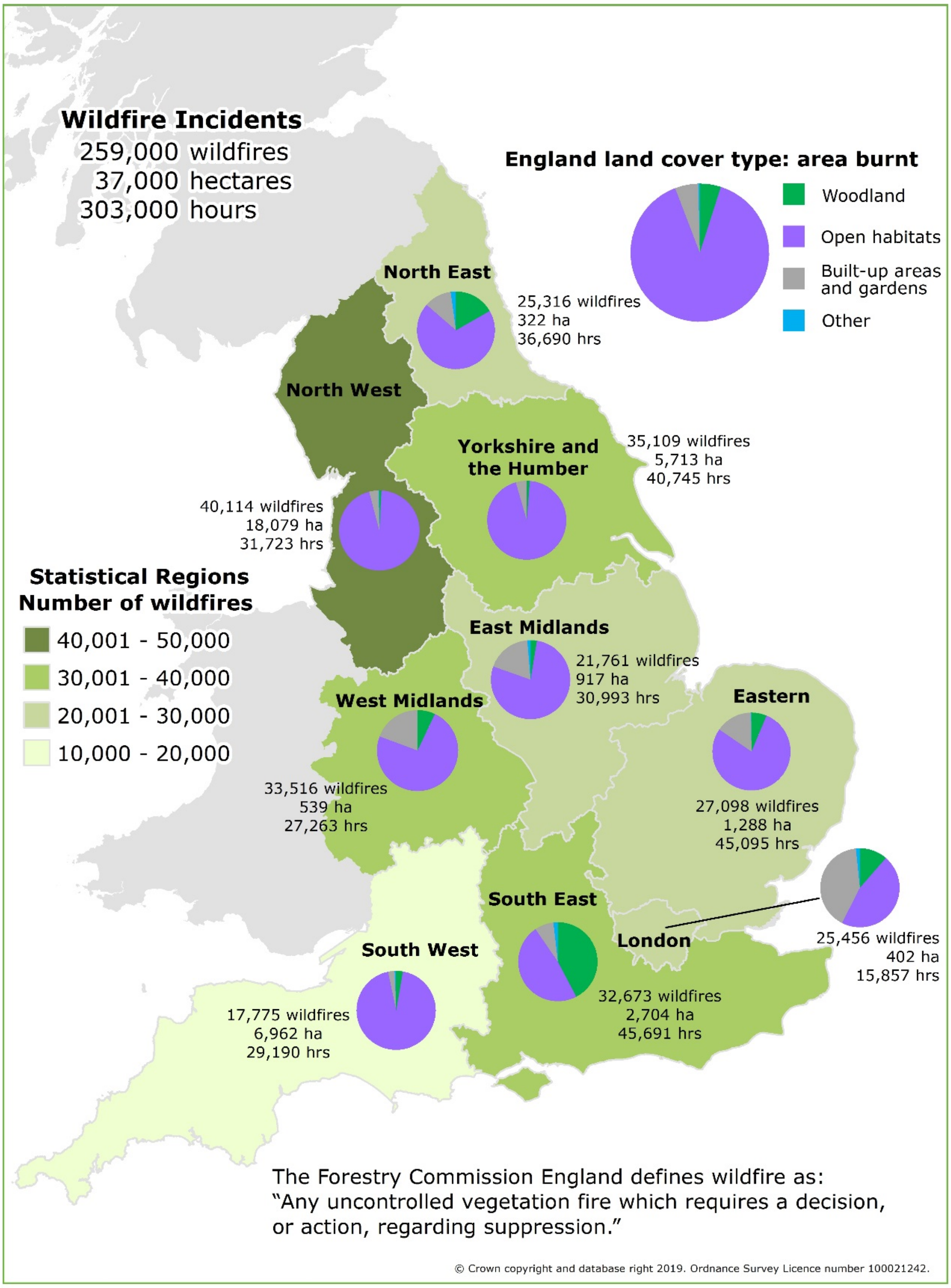


Figure 2. The distribution of wildfire incidents, areas affected and duration by English Regions 2009/10–2016/17 (from Forestry Commission England 2019 with permission).

h. Strong evidence of a high incidence of wildfires in south *Wales*, where there were over 55,000 “grassfires” (including *Molinia*) and nearly 550 forest fires recorded over eight years (2000–2008, para. 4.7b) which was reported as “equat[ing] to eight times more per unit area than in the UK as a whole” (Jollands *et al*. 2011 [2+]), though data were not given on the area of wildfires.

i. Strong evidence that wildfires are frequent in the *English* Peak District, with over 400 fires recorded by National Park rangers over a long 33-year period (up to 2008, para. 4.7d), reflecting the high visitor numbers and density of potential access-related ignition sources combined with what were considered to be “vulnerable moorland habitats” which make the National Park “extremely susceptible to wildfire during prolonged dry periods” (McMorrow *et al*, 2009 [2+] and Moors for the Future 2009 [2+], though see para. 9.9 regarding wildfire occurrence in East Midlands region).

Seasonal, monthly and other timing in the UK

4.15 There is strong evidence that peaks in, and coincidence of, at least some risk factors (para. 4.11) are associated with increased wildfire incidence in the UK in summer and especially spring (McMorrow *et al*. 2009 [2+], de Jong *et al*. 2016 [2++], Jollands *et al*. 2011 [2+], Krivstov & Legg 2011 [2+], Davies & Legg 2016 [2+], Martin 2018 [3+] and Appendix 2 [2+]; and Figure 3). This includes strong or moderate evidence from the following national, regional and local data sets and studies of a strong seasonal pattern, with a marked spring peak, especially in April and in the uplands, which extends generally at a lower level through summer (but with periodic weather-related peaks in some years), with much lower frequency in autumn and winter:

a. Strong evidence from an analysis of 2,921 ‘NOGP-type’ wildfires in *GB* over three years (2010–12, para. 4.7a), that the majority (59% of events and 95% of the burned area) occur in spring, with events in summer the next most frequent (24% of events, but only 4% by area), with few in autumn (13%) and winter (3%) which contribute very little to the total area burned (0.8 and 0.1%, respectively) (de Jong *et al*. 2016 [2++]).

b. Strong evidence from recent *English* wildfire data held by and submitted to Natural England (from 3,127 fires, mostly over eight years 2011–2018, para. 4.6), of a marked seasonal pattern in wildfires, with peaks in spring (48% of fires) and summer (34%), and fewer in autumn (14%) and especially winter (5%) (Appendix 2 [2+]; also see Figure 3).

c. Strong evidence also from the same recent *English* wildfire data of a difference in the seasonal pattern of wildfires between lowland and upland areas (Figure 3 and Appendix 2 [2+]). In the lowlands, there is a more even spread over the spring (44% of lowland fires) and summer (35%) peak, with more in autumn (15%) and winter (6%) than in the uplands. In the uplands there is a more marked spring peak (67% of upland fires) with fewer in summer (25%, the majority, 78%, in just three peak years, 2010, 2013, 2018), autumn (6%) and winter (2%) (Figure 3a), though more fires occurred in the lowlands in total in this data set (2,643 fires, 85% of all fires) and in all seasons (Figure 3b).

d. Strong evidence from the same recent *English* wildfire data (from a subset of 3,047 fires with accurate dates, mostly 2011–2018), that within the seasonal pattern, the frequency of fires is greater between March and September (more than 8% of the total number of fires over the year in each month c.f. mean of only 2% between October and February) and especially from April to June (all months >13% of all fires) (Appendix 2 [2+]). The spring peak is particularly pronounced in April (21% of fires), especially in the uplands (32% c.f. 19% in the lowlands) where a high percentage also occur in May (20% c.f. 15% in the lowlands). Thus, in the lowlands fires are much more evenly spread over the spring and summer months with between 11 and 15% in all months between March and August.

e. Strong evidence from a sub-set of the national IRS *English* wildfire data for ‘upland’ areas (657 fires covering 9,523 ha, 2009/10–2016/17, para. 4.4) that the majority of wildfires occur in spring (March-May, 68% of all upland wildfires), especially in March and April (52%), compared to summer (June-August, 21%), autumn (September-November, 8%)

and winter (December-February, 4%) (Figure 4, Forestry Commission 2019b [2++] and Appendix 2 [2+]).

f. Strong evidence from an analysis of 4,343 FRS 'all wildfire' incidents (2003–2007, para. 4.14g) of a peak in wildfire incidents in *Scotland* in spring, followed by summer, with fewer in autumn and least in winter (Davies & Legg 2016 [2+]).

g. Strong evidence from FRS data from vegetation fires (55,331 'grassfires' and 527 forestry fires) in south *Wales* (2000–2008, para. 4.7b) of a marked spring peak in 'grassfire' and forest fire incidence, from March to May, with most in April. There is a lower incidence in summer, with occasional weather-related peaks, and far fewer incidents in autumn and winter, though there is some variation in this pattern between years (Jollands *et al*. 2011 [2+]).

h. Moderate evidence, more locally, from 22 "main" wildfires on Darwen and Turton Moors (mostly blanket bog) in the *English* West Pennines over 22 years (1995–2017), that all but one occurred between late-winter and spring (Martin 2018 [3+]). The late-winter/spring fires all occurred between 23 February and 22 April, apart from one from 13–15 May, with the mean day of the year 30 March and median 24 March. The vast majority were in the six-week period from 9 March to 22 April.

4.16 There is moderate evidence of slightly increased wildfire incidence at weekends and during school and bank holidays, probably associated with increased levels of public access and both accidental fires and arson (McMorrow *et al*. 2009 [2+], Jollands *et al*. 2011 [2+], Cavan *et al*. 2006 [3+] and Appendix 2 [2+]). This includes moderate evidence from:

a. Recent *English* wildfire data from 3,127 fires (2011–2018, para. 4.6), of a relatively even distribution of fires by day of the week, but with a slight increase at weekends and on Mondays (16%, 18% and 16% of fires, respectively, compared with a mean of 13% on other days) (Appendix 2 [2+]).

b. FRS data from vegetation fires in south *Wales* (55,331 'grassfires' and 527 forestry fires, 2000–2008, para. 4.7b), of a similar slightly increased incidence on Saturdays, Sundays and Mondays (18%, 15% and 15% respectively c.f. 12–14% on other days), though there was some monthly variation, with a higher relative percentage occurring in mid-week in summer (Jollands *et al*. 2011 [2+]).

4.17 There is moderate evidence from FRS data from vegetation fires in south Wales (para. 4.14h above), that incidence of fires builds steadily through the day peaking in the late-afternoon/early-evening between 16:00 and 19:00 hours, later at around 18:00 on weekdays (Monday to Thursday), than at weekends (around 17:00, Friday to Sunday) (Jollands *et al*. 2011 [2+]). Throughout the mid-spring/summer months (April to August) the percentage of fires recorded later in the evening increases, suggesting "… that fires start outside work and school hours [and] … a link between the timing of fires and the daily routines of firesetters" in a deprived area where most fires were attributed to arson close to access points (para. 5.35).

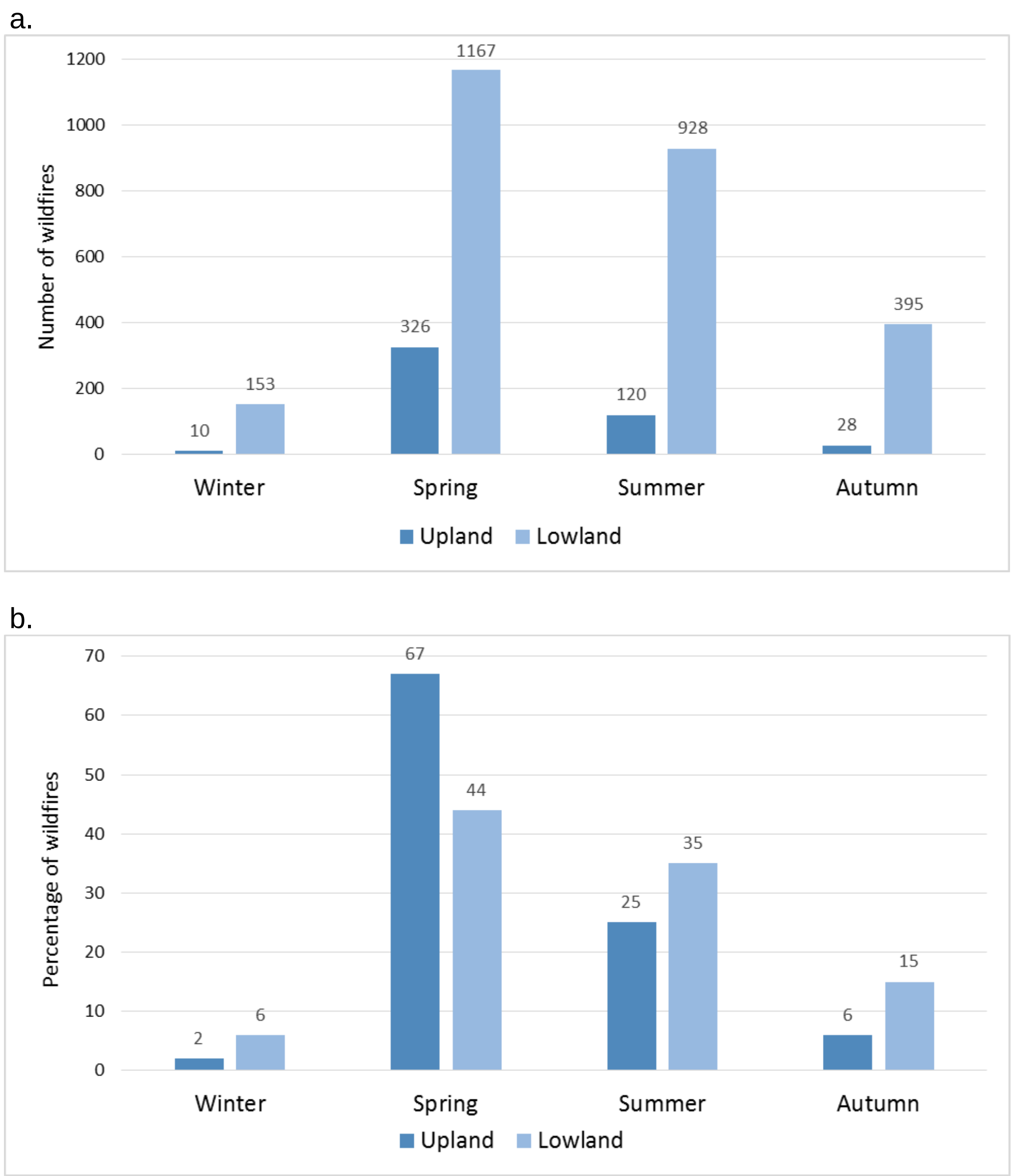


Figure 3. The number (a) and percentage (b) of upland (*n* = 484) and lowland (*n* = 2,643) wildfires by season from Natural England and other submitted English data 2002–18 (mostly 2011–18) (Appendix 2 [2+]).

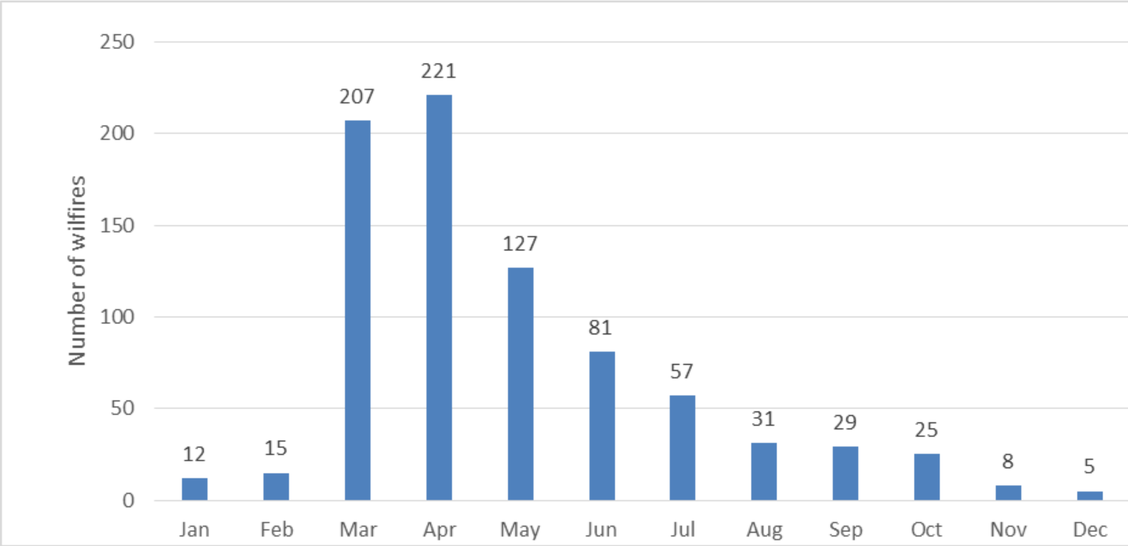


Figure 4. Monthly distribution of wildfires from a sub-set of English wildfire data from the IRS data set for ‘upland areas’ (*n* = 657 fires covering 9,523 ha) 2009/10–2016/17 (Forestry Commission 2019 [2++], para. 4.4 and Appendix 2 [2+]). Upland areas were defined as ‘mountain, heath and bog’, and ‘semi-natural grassland’ land cover categories above 250 m *and* in the Defra Moorland Line.

Weather and trends in wildfire occurrence the UK

4.18 The UK has a relatively uniform annual rainfall pattern with no regular dry season, “though short droughts of [a month or more] often occur that can lead to catastrophic wildfires” (Murgatroyd 2002 [3+]). There is strong evidence that the incidence of wildfire, especially large wildfires, in GB is episodic, coinciding with dry-spells, especially droughts, and hot periods (para.4.11), with much variation between years (Forestry Commission England 2019 [2++], McMorrow *et al*. 2009 [2+], Albertson *et al.* 2010 [2+], Perry 2019 [2+] and Cavan *et al.* 2006 [3+]) which makes determination of temporal trends (and forecasting) difficult, especially as collation of data nationally is relatively recent (para. 4.3). This includes the following strong and moderate evidence from national, regional and local studies:

a. Strong evidence from an analysis of recent wildfires attended by the FRS in *England* recorded in the IRS database over eight years (2009/10–2016/17, para. 4.3), of relatively wide annual fluctuations, but no clear temporal trend, in the annual frequency of ‘all wildfires’ over the period, with peaks of between 46,340 and 48,847 incidents in the first three years linked to a drought between 2010 to 2012 and between 17,099 and 24,393 in all other years apart from 30,657 in 2014/15 (Forestry Commission England 2019 [2++]). A similar pattern was evident for the area burned per year, with peaks in the first three years (range 4,827–14,043 ha) and less variation in all other years (range 1,095–2,246 ha), resulting in a total of 36,916 ha burnt over eight years (mean 4,615 ha/year).

b. Strong evidence of similar annual fluctuations in the number of (the far fewer) NOGP wildfires in *England* (range 447–1,168/year) from the same IRS database, though with less variation in the numbers of incidents, with between 1,075 and 1,168 in the first three peak years, and between 743 and 918 in all other years apart from a low of 447 in 2012/13 probably reflecting heavy rain in spring 2012 (Forestry Commission England 2019 [2++]). The pattern for area burned is more variable between years and very similar to the area totals for ‘all wildfires’ (4,587–13,774 ha in first three years and 1,001–2,131 ha in all other years c.f. para 4.18a above for ‘all wildfires’), indicating, as would be expected, that most larger wildfires are NOGP fires and that ‘all wildfires’ includes a very large number of small, probably mostly urban and rural-urban interface fires.

c. Strong evidence from an analysis of operational Met Office Fire Severity Index outputs for *England* and *Wales* (para. 7.22 and 7.30) that the summer of 2018 saw “… more extensive, long-lasting and more severe fire weather conditions [than in] the previous four years" for which records were available and (from satellite-derived burn area data over a longer, 15 year period back to 2003) the largest area burnt, and hence was an "unusually extreme but not unprecedented year for wildfires, with the burnt area being slightly greater than, but comparable to, previous severe fire years such as 2003 and 2006" (Perry 2019 [2+]).

d. Moderate evidence of annual variation in the frequency of wildfire incidents in a *Scotland*-wide analysis of Fire and Rescue Service records over five years (2009/10–2014/15) which identified 233 'primary' wildfires with a range from 25 (2009/10) to 60 per year (2011/12), with, not surprisingly over the short period, little evidence of any temporal trend (Luxmoore 2018 [2+]).

e. Moderate evidence from 22 'main' wildfires on Darwen and Turton Moors in the *English* West Pennines between 1995 and 2017, that most (13, 59%) occurred during easterly winds (SW is the prevailing direction), perhaps associated with drying conditions (Martin 2018 [3+]). This is supported by Cavan *et al*. (2006 [3+]) who also linked wildfire occurrence with particular wind directions, especially easterlies.

f. Moderate evidence from an analysis of the incidence of over 55,000 'grassfires' recorded in south *Wales* (2000–08) in relation to weather data, of a reduction in wildfire incidence during periods of rainfall (though fire incidence often increases not long after rainfall ceases) and an increase in frequency as temperature increases (Jollands *et al*. 2011 [2+]).

g. Moderate evidence from a review of climate change and the visitor economy which noted, in relation to moorland wildfires in the *English* Peak District, that "risk of fire increases with daily maximum temperature, and dry spells also cause extra fire hazard, since current and past rainfall reduces fire risk" (Cavan *et al.* 2006 [3+]).

4.19 Further information on the relationship between wildfire occurrence and weather is given in the sub-section on the Met Office Fire Severity Index (paras. 7.21–7.32).

Moisture content of vegetation in the UK

4.20 Related in part to weather and also to season, habitat, plant and fuel type, and phenology, there is strong evidence from the UK that risk of ignition and spread is heightened when vegetation fuel moisture content in the typically *Calluna* canopy and/or bryophyte/litter layer is relatively low or reduced in response to cold weather (Davies *et al*. 2010 [2++], Grau-Andrés *et al*. 2018 [2++], Davies 2005 [2+] and Davies & Legg 2011 [2+]), for example, where moisture content of *Calluna* is around 60% or lower and 140% or lower for the bryophyte layer (Davies & Legg 2011 [2+]). This is also supported by moderate evidence that:

a. In the *UK* physiological drought may be caused by cold, clear weather and frozen ground, and winter cuticle damage, which can reduce the fuel moisture content of live biomass and create the potential for ignition and extreme fire behaviour, particularly in spring (Davies *et al*. 2010 [2++] and Davies 2005 [2+]).

b. Reduced fuel moisture content of moss/litter and soil in a *UK* heath led to increased fire-induced consumption of the moss/litter layer and increased soil heating compared to a raised bog site, leading to increased fire severity (Grau-Andrés *et al*. 2018 [2++]).

4.21 Little evidence was identified on temporal and spatial trends in fuel moisture content or for vegetation types dominated by species other than *Calluna*.

Habitat, vegetation and land use types

4.22 There is strong evidence that wildfires in GB occur relatively widely and cover the greatest area on open, semi-natural habitats, especially moorland habitats (including upland heathland

and peatland) and lowland heathland, and to a lesser extent on semi-natural grasslands, though the frequency of incidents (but not area) is greater on woodland, agricultural land ('improved' grassland and arable) and especially in urban areas (de Jong *et al*. 2016 [2++], Forestry Commission England 2019 [2++], McMorrow & Lindley 2006 [2+], McMorrow *et al*. 2009 [2+] and Aylen *et al*. 2007 [3+]). This includes the following strong and moderate evidence:

a. Strong evidence from an analysis of land cover types (principally from Land Cover Map 2007, Morton *et al*. 2011) on which 2,921 'primary' wildfires occurred in *GB* between January 2010 and December 2012, from the Incident Recording System (IRS) database (para. 4.7a), that, whilst wildfire incidents were most frequent on grassland (33% of incidents) and arable and urban (both 19%, though only 4% by area) land cover types, by far the largest area (50% from just 11% of incidents) occurred on 'heath/bog/marsh', with the next largest area on grassland (24%) (de Jong *et al*. 2016 [2++]).

b. Strong evidence from an analysis of land cover types (from Land Cover Map 2007, and 2015, Rowland *et al*. 2017) on which recent wildfires in *England* were recorded in the IRS database (eight years 2009/10–2016/17, para. 4.3), that incidents ('all wildfires', 258,867 incidents) were most frequent on built-up areas and gardens (50%), improved grassland (17%), woodland (16%) and arable land (12%), with much lower percentages on open, semi-natural habitats (5% in total): semi-natural grassland (3%), mountain, heath and bog (0.9%) and coastal, freshwater and saltwater combined (0.8%) (Forestry Commission England 2019 [2++]). However, the majority by area occurred on open, semi-natural habitats (59%) comprising: mountain, heath and bog (48%), semi-natural grassland (11%) and coastal, freshwater and saltwater combined (0.3%). The remainder were on improved grassland (18%), arable (11%), woodland (9%) and built-up areas and gardens (4%) (Forestry Commission England 2019 [2++]).

c. Strong evidence from an analysis of recent incidents ('all wildfires') in *England* recorded in the IRS database (eight years, 2009/10–2016/17, para. 2.3) that wildfires significantly affect designated sites, with a total of 7,042 incidents covering 10,320 ha (mean 1,290 ha per year) in SSSIs and smaller numbers and areas in SACs (2,677, 8,386 ha), SPAs (2,874, 5,496 ha) and Ramsar Sites (1,203, 225 ha) (Forestry Commission England 2019 [2++]). National Parks are similarly affected, with 2,944 incidents covering 6,940 ha (mean 868 ha per year).

d. Moderate evidence of differences in the incidence of wildfires between different moorland habitats in the *English* Peak District, UK, with "heather moorland" (probably comprising heather-dominated heath *and* bog) less prone to the occurrence of wildfires than other moorland habitats (McMorrow *et al*. 2009 [2+]). On the other hand, the three habitats found to be at most risk of experiencing wildfire were areas with "bare peat, eroding moor and bare ground" interspersed with grass and dwarf-shrub patches (McMorrow & Lindley 2006 [2+] and Aylen *et al*. 2007 [3+]), while fires were far less likely in "wetter habitats such as [cottongrass] *Eriophorum* bog" (Aylen *et al*. 2007 [3+]).

e. Moderate evidence from south *Wales* that the majority of grassfires occurred on "semi-improved neutral grassland" (though [acid] "*Molinia* grass[land]" is also mentioned in the report so may be included), while the majority of forestry fires were recorded in "planted coniferous woodland" (Jollands *et al*. 2011 [2+]).

4.23 There is moderate evidence that the flammability of peat/litter fuel-beds on UK heathland/moorland differs depending on the intrinsic characteristics of the species making up the fuel layer. In the upper canopy layer, often composed mainly or solely of *Calluna*, the probability of ignition is influenced by the proportion of dead fuel accumulated within the vegetation and the moisture content (Santana & Marrs 2014 [2++]). Older *Calluna* stands "have a high biomass of woody matter and hence represent a wildfire hazard due to their high fuel load" (Aylen *et al*. 2007 [3+]). However, there is limited evidence on flammability of other UK species/vegetation types.

4.24 There is moderate evidence from continental **Europe** and **North America** that 'pristine' and 'less-modified' peatlands, especially where the water table is high, are less vulnerable to severe, smouldering fires (Granath *et al*. 2016 [2++] and Turetsky *et al.* 2014 [2+]). This includes moderate evidence that:

a. "Because of high moisture contents, the bulk of peat soils in pristine peatlands is naturally protected from burning …" and that "the major current … issue is with shallower, drained, degraded and mined peatlands, especially in boreal forests, where drainage and climatic drying enhances microbial decomposition of organic soils and stimulates fire activity" (Turetsky *et al.* 2014 [2+]).

b. Rewetting and restoration of **Canadian** and **Scandinavian** peatlands can effectively lower the risk of such burns, especially if a new *Sphagnum* bog-moss layer is established which raises peat moisture content, though without the recovery of a *Sphagnum* layer, rewetting alone is insufficient to reduce the risk of deep burning unless the water table remains at the peat surface (Granath *et al*. 2016 [2++]). (Linked to this, also see paras. 6.12 in the section on severity (6) on differences in burn severity between habitats in the UK and elsewhere (including more severe burns on dry heath and woodland) and paras. 7.8–7.9 on the effects of habitat restoration, especially rewetting, in the section (7) on prevention.)

4.25 There is moderate evidence from a study of wildfire of **Australian** savannas that the frequency and season of fires varies with grass composition and distance from settlement, with the cover of annual grasses a stronger correlate of fire activity than grass biomass, suggesting that fuel connectivity may be the more critical feature in the spread of fire (Elliott *et al* 2009 [2+]). Grass cover was found to be a useful proxy for fuel connectivity, which may also be provided by litter from trees and shrubs.

Extent and size of wildfires in the UK

4.26 There is strong evidence that NOGP/NOGP-type wildfires in GB are widespread and relatively extensive, covering, for example, 17,203 ha/year in GB over a three-year period (2010–12) and 4,434 ha/year in England over eight years (2009/10–2016/17), with the vast majority small in size, e.g., 99% less than 1 ha in England, with large, very large and landscape scale fires, and fires on semi-natural habitats (para. 4.22b), accounting for a disproportionate high proportion of the area burnt (de Jong *et al*. 2016 [2++], Forestry Commission England 2019 [2++], Appendix 2 [2+] and Martin 2018 [3+]). However, data on total area burnt by size class were only available for an upland sub-sample of the IRS data set submitted by the Forestry Commission (2019b, para. 4.4).There is considerable annual variation in the area burned (para. 4.18a,b) reflecting episodic, heightened fire weather, with data required over a longer period to better assess any trends the area subject to wildfire. This includes the following strong and moderate evidence:

a. There is strong evidence from an analysis of 2,921 NOGP-type wildfires in *GB* (over three years January 2010–December 2012, para. 4.7a), that wildfires burned a total area of 51,609 ha, giving a mean of 17,203 ha/year (over a short three-year period) and mean burn size of 18 ha, though burn area is skewed by the much greater frequency of smaller fires and the median was estimated to be only 2.5 m^2 (de Jong *et al*. 2016 [2++]). The area burned varied markedly by season, with by far the largest area in spring (95% of the total area burned), and much smaller areas in summer (4%), winter (1%) and autumn (0.8%) (para. 4.15a).

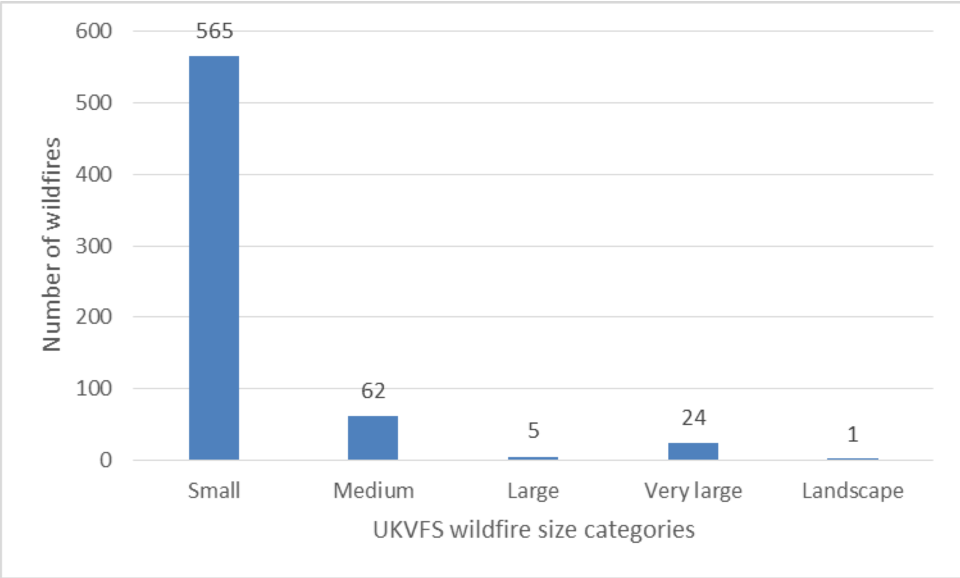
b. There is strong evidence from an analysis of 6,725 recent NOGP wildfires in *England* with burn size recorded in the IRS database (eight years, 2009/10–2016/17, para. 4.3) that a total of 35,470 ha was burned (mean 4,434 ha/year, mean burn size 5.3 ha), with the vast majority of incidents in the 'small' (<1 ha, 155,957 incidents, 99%), few in 'medium' (1–49 ha, 894, 0.6%) and very few larger: 'large' (50–99 ha, 24, 0.02%), 'very large' (100–999 ha, 45, 0.03%) and 'landscape scale' (>1,000 ha, 5, 0.003%) UKVFS fire size categories (Forestry Commission England 2019 [2++]).

c. There is strong evidence from recent *English* wildfire data from 183 fires on open, semi-natural habitats (compiled by Natural England over seven years 2012–18, para. 4.6) that such fires tend, as might be expected, to be larger than in the more comprehensive national FC-analysed IRS data set across all habitats/land uses (para. 4.26b), with most falling into ‘medium’ (59% of fires) or ‘small’ (28%) UKVFS fire size categories, but, as with the national data set, far fewer ‘large’ (3%), ‘very large’ (8%) or ‘landscape-scale’ (≥1,000 ha, 2%) incidents (Appendix 2 [2+]). Though there were more fires in the lowlands, there were slightly fewer in the largest size categories than in the uplands (Appendix 2 [2+] Natural England data 2011–18). Larger fires can, of course, cover much larger areas when they occur, but tend to be episodic (para. 4.18); although ‘very large’ and ‘landscape-scale’ fires occurred in four of the seven years, there was more than one such fire in only two years: 2011 (9 such fires) and 2018 (6), corresponding with peak wildfire years (Appendix 2 [2+]; also see Appendix 8).

d. More locally, there is moderate evidence from 22 “main” wildfires over 22 years between 1995 and 2017 on Darwen and Turton Moors in the *English* West Pennines, UK, that most burns were relatively large (medium or large UKVFS fire size categories) with the range 33–250 ha and mean 65 ha (from data given by Martin 2018 [3+]). This resulted in a total of around 1,480 ha being burned over the period, though some areas were repeatedly burned. “Practically the whole of the moors” were burned in May 1984, and since then the majority, but not all, of the area was again burned at some time up to 2017, though the extent burned reduced over the more recent period, it was suggested in response to agreed burning plans under agri-environment agreements.

4.27 Data on the total area burnt by wildfire size class are only available for an upland sub-sample of the IRS data set submitted by the Forestry Commission (657 fires covering 9,523 ha, 2009/10–2016/17, para. 4.4). This shows that despite the vast majority of fires being small (86% of fires) with medium (9%) the only other category with greater than 4% of fires, the *area* burnt was greatest in the very large (73%) and landscape scale (16% from only one fire), with no other size categories contributing more than 7% of the area (Figure 5, Forestry Commission 2019b [2++] and Appendix 2 [2+]). This supports the suggestion by de Jong *et al*. (2016 [2++]) that very large and landscape scale fires (para. 4.26), and fires on semi-natural habitats (para. 4.22b) such as moorland, account for a disproportionately high proportion of the total area burnt.

a.



b.

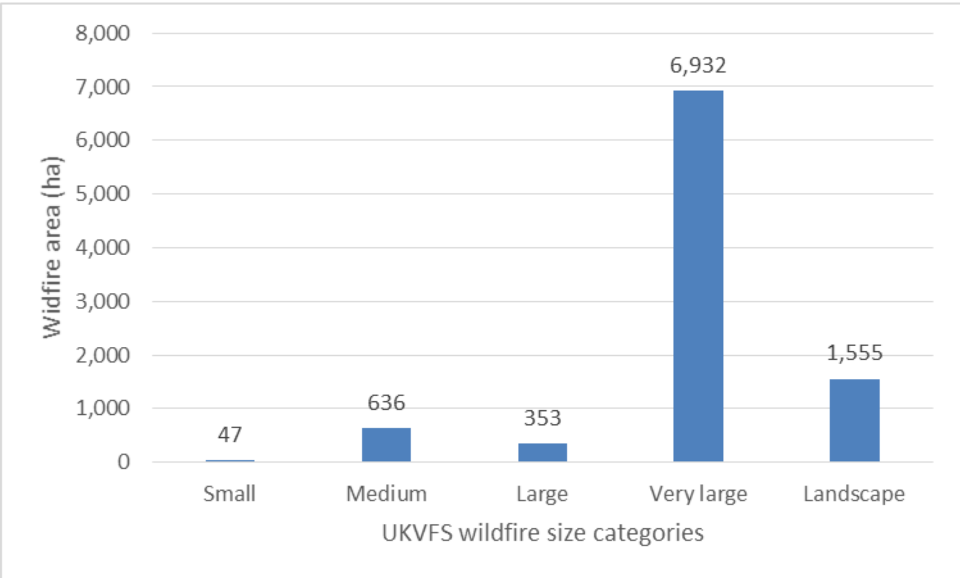


Figure 5. The number (a) and total area (b) of upland wildfires by UKVFS wildfire size category (Gazzard 2009) from a sub-set of English data from the IRS data set for 'upland areas' (*n* = 657 fires covering 9,523 ha) 2009/10–2016/17 (Forestry Commission 2019 [2++], para. 4.4 and Appendix 2 [2+]). Upland was defined as 'mountain, heath and bog', and 'semi-natural grassland' land cover categories above 250 m and in the Defra Moorland Line.

Evidence gaps and research recommendations on wildfire risk and occurrence

4.28 Assessment of the available evidence summarised above suggests that the following areas would benefit from further research, monitoring or other investigation:

a. Where possible, standardisation of the range of variables recorded and definitions used, particularly for cause of ignition, between the Home Office's national Incident Recording Scheme (IRS) and other wildfire recording schemes to improve compatibility of data nationally.

b. Improved recording of wildfires not attended by the Fire and Rescue Service, and hence not included in the IRS, using new or existing recording systems, for example those maintained by Natural England and the MOD.

c. Extension of the main analyses done so far using the IRS to further explore the occurrence of wildfire in England (and potentially the rest of GB/UK) and factors that may influence this and its severity, extent and impact. Specifically, this should include the timing (e.g., weekly/monthly/seasonally), cause (ideally using agreed definitions/classification), and specific habitat (e.g., using Natural England's Priority Habitat Inventory) and land use types affected.

d. Further exploration, and potentially modelling, of factors associated with the occurrence of wildfires using the IRS and additional data sets held by government (e.g., MOD and Natural England) and other organisations.

e. Wider exploration of the effect of weather events and climate on wildfire occurrence and extent using existing weather, climate and wildfire data.

f. Review and extension of the potential use of Earth Observation data to improve wildfire mapping and characterisation (e.g., of severity, Schepers *et al*. 2014 and Scottish Natural Heritage 2018), perhaps linked to existing GIS data sets. This could assist in addressing other recommendations regarding occurrence, severity, extent and impact.

g. Incorporation of socio-economic aspects in consideration of monitoring and research on their occurrence, severity, extent and impact, and in wildfire prevention and management/control (reducing impact). This could be done separately or ideally be integrated with biophysical research, but in either case, the findings ought to be interpreted holistically. It should involve engagement with the wildfire community, other stakeholders, land managers and the public.

h. Investigation of the relationship between routine managed burning and prescribed burning (and cutting/mowing and other management with a fuel management objective), and wildfire occurrence, extent, and ideally severity and impact. This should consider the potentially beneficial effect of fuel management and how factors such as the scale, pattern, frequency and targeting (in relation to risk factors) affect this, and the effect of burns escaping control resulting in wildfires and the factors that contribute to and cause loss of control. The latter could include consideration of indirect effects such as effects of managed/prescribed burns on vegetation composition (e.g., dominance of potentially flammable vegetation types) and water table (lowering).

i. Extension of recording/mapping of managed/prescribed burning in England potentially using Earth Observation, particularly in the uplands, in part to contribute towards investigation of the relationship with wildfire occurrence.

j. Similar to (h) above and potentially linked to restoration, carry out a broader investigation of the effects of wider management interventions, e.g., grazing, scrub and bracken management, and drainage, on wildfire occurrence, severity, extent and impact.

k. In reviewing factors associated with wildfire severity and impact, potential impact also needs to be considered. This includes inputs (e.g., guidance and effectiveness) to risk registers, and tools developed for wildfire management planning including risk assessment, scoring and mapping and fuel mapping.

l. Development of an approach to recording burn severity using a simple on-the-ground method of assessment, potentially for use in wildfire recording schemes, and/or based on Earth Observation.

m. Research into the influence of sward composition and structure on the occurrence, severity, extent and impact of wildfire, particularly for dominant species other than *Calluna*.

5 Wildfire ignition sources

5.1 The full text of question 2 is:

What are the main wildfire ignition sources?

Introduction

5.2 The risk and occurrence of wildfire is covered under the previous section (4), though human-related factors, which tend to link more directly to ignition, are mainly covered in this section which deals with the causes of ignition and initial spread of wildfires. Other aspects of wildfire behaviour, including spread, are covered under the next section on fire behaviour and severity (6). Ignition is usually classed as natural (principally from lightning strikes), accidental or deliberate, i.e. arson (Figure 1 adapted from Prestemon *et al*. 2013 [3+]).

5.3 Data on the causes of ignition in the UK are limited, for example, it is not reported in the main analysis of the IRS data set by Forestry Commission England (2019), with most available from the Natural England and other submitted English data sets (para. 4.6, Appendix 2 [2+]). Even in these data sets, 15% of incidents did not have a cause assigned and most were given only by broad, “accidental” or “deliberate” categories, with more precise data on cause only available for a minority (12%) of incidents. It can be difficult to determine cause, especially without standard, defined categories. Hence, it may represent a subjective judgement, particularly in relation to more precise causes. There may also be bias due to potential reluctance to identify and report the cause of wildfires. The Natural England and submitted data sets appear to lack standardised categories for more precise causes, which resulted in the need to amalgamate similar types of cause such as various types of campfires and other small fires getting out of control (e.g. Figure 6 and Appendix 2 [2+]). In addition, the cause of ignition is only one of the series of linked factors that together lead to a wildfire occurring (Figure 1).

Summary of evidence on wildfire ignition

5.4 This section initially summarises evidence on general causes of wildfire ignition and the association with access and proximity to habitation and development, and then the main individual cases of ignition in the UK and to some extent elsewhere.

General wildfire ignition sources

5.5 Ignition occurs when the temperature of potential fuel is raised in presence of oxygen above a critical level, which for most vegetation is between 325–480 °C (Pyne *et al*. 1996 [2++], Santana & Marrs 2014 [2++] and Davies & Legg 2011, 2016 [both 2+]).

5.6 There is strong evidence that when conditions lead to risk of a wildfire event, most ignitions in the UK are anthropogenic in origin, either ‘accidental’, associated with concentration of public access, recent/current wildfire or managed burning activity, or deliberate (arson), with very few documented instances of ‘natural’ wildfires due to lightning strikes (de Jong *et al*. 2016 [2++], Davies & Legg 2011, 2016 [both 2+], Gallani 2002 [3-], Bruce 2002 [3+], Appendix 2 [2+] and para. 5.13). This includes the following evidence:

a. Strong evidence from recent (mostly 2002–18) *English* wildfire data held by and submitted to Natural England (Appendix 2 [2+]) that, where a broad cause of fire was assigned (2,726 fires), the majority (77%) were classed as deliberate and the minority (23%) accidental (excluding 492 (15%) where a cause was not assigned). There was a marked difference in the percentage classed as deliberate between the lowlands (80%) and uplands (55%), though the majority of fires were in the lowlands (88%), where they tended to be smaller in area (para. 4.26c). The percentage classed as cause unassigned was higher in the uplands (35%) than the lowlands (11%).

b. Strong evidence from the same recent *English* wildfire data (Figure 6 and Appendix 2 [2+]) that, in the minority of cases when a more specific cause was assigned (382, only 12% of all fires), the main causes were 'camp fires' (49%), land management burns (15%), barbeques (10%), and 'reignited' fires and military training (both 5%) with no other individual causes greater than 3%. There were again differences between the lowlands, where the pattern was more similar to that overall (reflecting the fact that the majority of fires with a specific cause assigned were in the lowlands) with most due to camp fires (56%), barbeques (11%), 'reignited' fires (8%) and land manager burns (8%), whereas in the uplands the majority were assigned to land manager burns (68%), followed by camp fires (9%) and barbeques (8%). Care is needed in interpreting these findings given the small proportion of overall fires where a specific cause was assigned and potential bias and subjectivity in these assessments (para. 5.3), and the relatively small number in the uplands (62, 10% of all upland fires) which emphasises the need for better recording of information about the causes of wildfire incidents. Further detail on some of these and other specific causes is given in the following sub-sections.

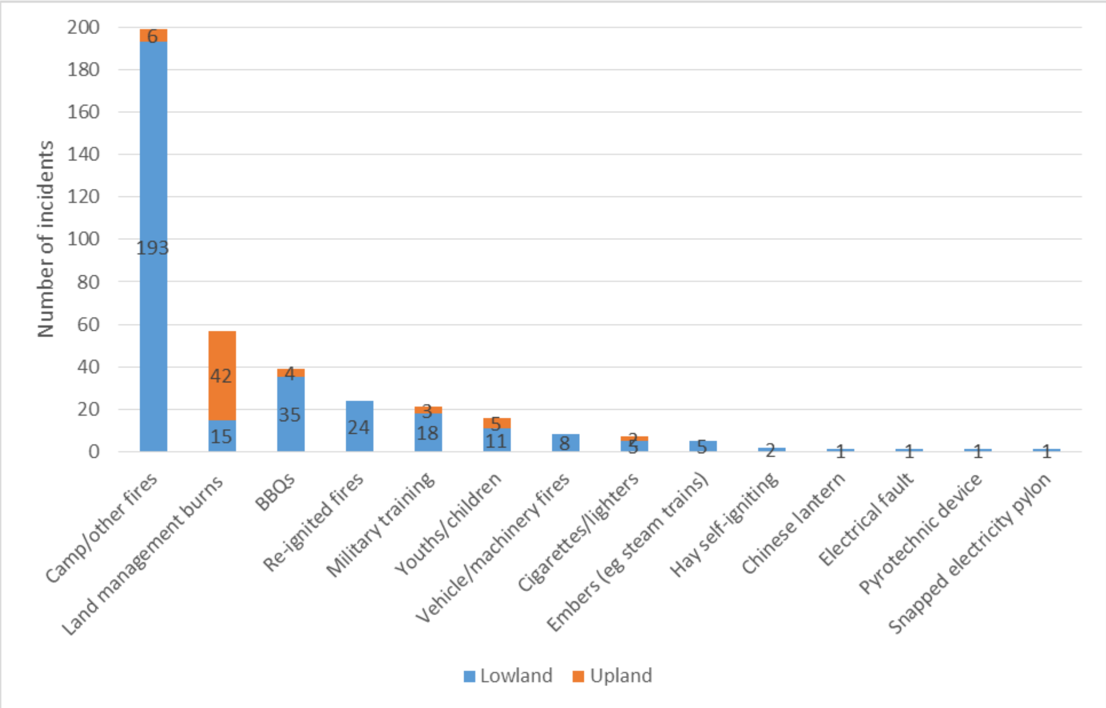


Figure 6. The number of ignitions where a specific cause was identified by lowland (*n* = 320) and (*n* = 62) upland areas from Natural England and submitted English wildfire data 2009–18 (Appendix 2 [2+]) based on amalgamated classes.

5.7 **Away from the UK**, there is similar strong evidence that most wildfires are anthropogenic in origin, with some specific accidental causes such as power lines and machinery more common, and lightning is a more frequent natural cause in some regions, especially the Tropics (Syphard & Keeley 2015 [2+], Shang *et al*. 2004 [2+] and Weber 2000 [3-]). In addition to lightning, natural ignitions can also potentially result from volcanic activity and geological friction (Ramos-Neto & Pivello 2000 [2+]). This includes strong evidence from a review of 'bushfires' in **Australia** that the majority are caused by humans either deliberately or through negligence (Weber 2000 [3-]). Fires were classed as either accidental/negligent or deliberate, with (a) accidental comprising: natural fires caused by lightning strikes, spontaneous combustion or glass; and (b) negligence caused by vehicles and/or trains, non-stationary engines, stationary engines, welding, grinding, soldering or gas cutting implements, fuel spill fires, powerlines, escape from campfires and cigarettes. Deliberate causes comprised or were indicated by: incendiary devices, close proximity to roads, numerous fires close together, evidence of human activity, previous fires in the same location, the method of ignition could not be determined and all accidental causes have been eliminated, evidence from eyewitnesses, and an apparent motive.

Association with access and proximity to habitation and development

5.8 There is strong evidence from an analysis of wildfires attended by the FRS in England from the UK IRS database over eight years (2009/10–2016/17, para. 4.3) that between 21% and 28% of all ‘primary fires’ per year occurred in built-up areas and gardens (Forestry Commission England 2019 [2++]).

5.9 There is strong evidence from an analysis of 55,000 ‘grassfires’ and nearly 550 forest fires in in south Wales (2000–08, para. 4.7b) that wildfires are associated with public access, especially on or near the rural/urban interface, with over 90% of ‘grassfires’ recorded within 100 m of a road or public right of way (PROW) and 99% within 500 m of a road or PROW (also see para. 5.35 regarding a similar link with deprivation) (Jollands *et al*. 2011 [2+]).

5.10 There is moderate evidence from the Peak District, UK, that fires are more frequent near to access routes such as roads and footpaths, and on certain days of the week, especially at weekends, and school and bank holidays, associated with increased levels of public access with, for example, a bank holiday in May being a particularly high-risk period (McMorrow *et al*. 2009 [2+] and Cavan *et al*. 2006 [3+]). More recent Moors for the Future Partnership data from the Peak District indicate a change in the distribution of where wildfires start, with them now (2009–18) more likely to start in more accessible areas on the fringes of the moorland, particularly in the NW, close to population centres, whereas in the past (1976–2003) they were more associated with high moorland areas particularly adjacent to the Pennine Way (Dixon & Chandler 2019 [2++]). This may perhaps reflect a change in visitor distribution and/or behaviour.

5.11 There is strong evidence from southern continental **Europe**, especially **Spain** and **Portugal**, and **North America** that most wildfire ignitions are human-related (Romero-Calcerrada *et al*. 2008 [2++], Catry *et al*. 2009 [2++], Ganteaume & Jappiot 2013 [2++], Faivre *et al*. 2014 [2++], Martinez *et al*. 2009. [2+], Martín-Fernández *et al*. 2013 [2+], Ricotta & Di Vito, 2014 [2+], Prestemon *et al*. 2010 [3++] and Shang *et al.* 2004 [2+]). This includes strong evidence that the most important indirect and direct human-related factors associated with wildfire ignitions include:

a. Access to the ‘natural’ landscape, especially proximity to urban areas and roads (Romero-Calcerrada *et al*. 2008 [2++]), and agrarian activities, land abandonment, rural exodus and development processes in **Spain** (Martín-Fernández *et al*. 2013 [2+]).
b. Population density and human accessibility, together with land cover, in **Portugal** (Catry *et al*. 2009 [2++]).
c. Human accessibility, including distance to road and housing, and urban development, with weather, weekends and holidays all factors in human-induced ignition in the **USA** (Prestemon *et al*. 2010 [3++] and Faivre *et al*. 2014 [2++]).

Lightning

5.12 In a review of lightning climatology in the UK and Europe Holt *et al*. (2001 [2+]) note that the maximum number of ‘thunder-days’ occurs in the summer months, generally with a greater number in SE England, but with an area of intense activity stretching NW across the Midlands towards Manchester and Liverpool. In winter, more lightning generally occurs over the sea than the land and is generally associated with precipitation. Corresponding with this, the number of lightning flashes is highest in summer, but with only about 1 km^{-2} yr^{-1} over and around the UK compared with up to 70 km^{-2} yr^{-1} in the tropics (Rycroft 2014 [2+]).

5.13 There is strong evidence that ‘natural’ wildfires in the UK due to lightning strikes are rare (Davies & Legg 2016 [2+], Gallani 2002 [3-] and Bruce 2002 [3+]) with only a few documented instances (e.g. Allison 1954 [3+] and a recent Northumberland case near Linhope in July

2018, Marjorie Davy, Natural England, in litt.) and none included in recent (2002–18) English wildfire data held by and submitted to Natural England (Appendix 2 [2+]).

5.14 **Away from the UK**, there is strong evidence that lightning-induced fires, particularly from 'dry' lightning with little or no precipitation, which is less common in the UK (para. 5.12 above), are more frequent in some regions and countries, particularly in the Tropics (Peterson *et al*. 2010 [2++], Woolford 2014 [2++], Vecín-Arias *et al*. 2016 [2++], Rorig & Ferguson 1999 [2+] and Pineda & Rigo 2017 [2+]), including the following evidence:

a. Moderate evidence from an investigation of the relationship between lightning fires and precipitation in Catalonia, **Spain**, that lightning-ignited fires (10% of all wildfires) are particularly associated with 'dry' lightning with little or no precipitation, or with low levels of precipitation, with 25% associated with no precipitation at all, 40% with less than 2.5 mm of precipitation (corresponding to 'dry' lightning), 60% with less than 4 mm and 90% with less than 10 mm (Pineda & Rigo 2017 [2+]). 'Holdover' fires (ignitions with delayed 'arrivals') are rare, with only 5% of lightning-ignited wildfires having a smouldering period of three or more days. The vast majority of lightning-induced fires occur in summer, with 95% between June and September, similar to 92% for Spain as a whole. It was noted that in other European studies from northern latitudes, lightening-induced fires occur from May to October, with the peak in July-August, whereas in the eastern Mediterranean, conditions are unfavourable in summer and, although lightning storms occur in winter, ignitions are generally extinguished by precipitation.

b. Moderate evidence from an assessment of lightning-induced fire occurrence for the central plateau of the **Iberian Peninsula** that the probability of a landscape being affected increased with the increasing percentage area of coniferous and mixed woodlands and the mean peak current of negative flashes whereas it decreased with increasing altitude and the percentage of agricultural crops (Vecín-Arias *et al*. 2016 [2++]).

c. Moderate evidence that lightning is the primary cause of wildfire in the forested regions of the Pacific Northwest of the **USA**, especially when it occurs without significant precipitation at the surface (Rorig & Ferguson 1999 [2+]).

d. Moderate, but slightly contradictory, evidence from analysis of fire occurrence patterns in **North American** eastern and western boreal forest regions between 2000 and 2006 that dry lightning strikes accounted for only 20% of total lightning strikes, but were associated with, and likely caused, 40% of fire counts (Peterson *et al*. 2010 [2++]). Locations with a high percentage of dry strikes commonly experienced an increased number of fire counts, though the mean number of fire counts per dry strike was more than 50% higher in the western boreal forest sub-region, suggesting a geographic and possible topographic influence.

e. Moderate evidence from a modelling study in Ontario, **Canada**, that lightning-induced forest fire risk increased significantly between 1963 and 2009 and was forecasted to increase by over 50% by the middle of this century in response to climate change (Woolford 2014 [2++]).

Hot metal particles and embers

5.15 Fuel beds can be ignited by hot metal particles (which can be generated by powerline interactions, friction of metal components, grinding, welding, overheated brakes, vehicle exhausts, and other sources of incandescent particles) and lofted flaming or glowing embers or 'firebrands' (from burning vegetation, wooden structures or material and interactions between powerlines and trees) (Fernandez-Pello *et al*. 2014 [2++] and Porterie *et al*. (2005 [2+]). Their occurrence affects not just ignition but also spread (Section 6), but they are dealt with here.

5.16 Fernandez-Pello *et al*. (2014 [2++]) separate such 'spot fire' ignition into three independent processes: 1) generation of particles; 2) flight of particles by plume lofting and/or wind drag; and 3) ignition of a fuel bed after the landing of the particle. Ignition of the fuel bed by the hot particle seems to be controlled by the heat losses to the surroundings by the particle, the fuel bed being heated, and the incipient solid reaction (smoulder) or gas reaction (flaming). Larger particles require a lower temperature to ignite fuel beds than smaller particles. Ignition mechanisms for larger particles are determined by surface temperature, whilst for smaller particles it is determined by the particle energy and surface temperature. It is suggested that sparks must accumulate for ignition of a fuel bed to occur. In the case of embers, smouldering is the easier form of ignition although flaming ignition can occur if the ember is flaming and air velocities are moderate.

5.17 There is moderate evidence from recent wildfire data held by Natural England and submitted to this review (Appendix 2 [2+]) that ignition from hot metal particles or embers is uncommon in England, though a small number of incidences were recorded due to steam trains (4 cases), agricultural machinery (2), motor-cross bikes (1) and pyrotechnic devices (1) (all ≤1% of the 382 cases where a specific cause was given).

5.18 There is moderate evidence from modelling that firebrand emission distance obeys an exponentially-decreasing distribution law with the number of firebrands landed per square metre downwind following a continuously-decreasing pattern across the impact area (Wang 2011 [2++] and Porterie *et al*. 2005 [2+]), though this is affected by the degree of heterogeneity in the system. For homogenous systems, the effect of firebrands is strengthened when the fire impact length decreases and the characteristic firebrand emission distance increases (as a result, jumps in the rate of spread appear and time oscillations in the burning area can occur), whereas for heterogeneous systems, this effect becomes weaker as the degree of disorder and the distance of firebrand emission increase (Porterie *et al*. 2005 [2+]).

5.19 There is strong evidence that hot metal particles and embers or firebrands can be carried relatively large distances by wind and are considered a frequent cause of fires in the **USA**, and have been reported from elsewhere, including **New Zealand**, **Australia**, **southern Europe** (Fernandez-Pello *et al*. 2014 [2++]) and **South Africa** (Rallis & Mangaya 2002 [2++]).

5.20 There is moderate evidence from modelling that firebrand (lofted flaming or glowing debris which can potentially ignite and spread wildfires, para 5.15–5.16) emission distance obeys an exponentially decreasing distribution law (Porterie *et al*. 2005 [2+]). For homogenous systems, the effect of firebrands is strengthened when the fire impact length decreases and the characteristic firebrand emission distance increases. As a result, jumps in the rate of spread appear and time oscillations in the burning area can occur. For heterogeneous systems, this effect becomes weaker as the degree of disorder and the distance of firebrand emission increase.

5.21 There is moderate evidence from modelling applied to a bushfire at an urban interface in Canberra, **Australia**, that during the period of fire spread and prior it burning out, the number of firebrands landing per square metre downwind followed a continuously decreasing pattern across the impact area (Wang 2011 [2++]). Embers from ignited pines were blown into an urban area resulting in the destruction of a number of houses within a distance of up to 500 m from the vegetation edge.

Cigarettes

5.22 Cigarettes are often suggested as a source of ignition in accidental fires though there appears to be little published evidence on their importance and frequency in the UK. Nevertheless, there is moderate evidence from recent wildfire data held by Natural England and submitted to this review (Appendix 2 [2+]) that wildfire ignitions caused by cigarettes are uncommon in England with only six cases identified (1.6% of cases where a specific cause was given) and one due to a cigarette lighter.

5.23 There is strong evidence of a large reduction of the frequency of ‘smoking-caused’ wildfires across national forests and grasslands in the **USA** between 1980 and 2011 (to 10% of the 1980 level in 2011) reflecting a reduction in smoking rates (resulting in a 9% reduction in ‘smoking-caused’ wildfires), a reduction in incidents in states with regulations introduced requiring self-extinguishing ‘less fire-prone’ (LFP) cigarettes (estimated 23% reduction compared to states without regulations) and through improvements in wildfire cause reporting (48% reduction suggesting that a proportion of past fires were incorrectly classified as caused by smoking) (Butry *et al*. 2014 [2++]).

5.24 The reduction due to regulations requiring LFP or ‘reduced ignition power or propensity’ (RIP) cigarettes which self-extinguish when left unattended is supported by strong evidence from ignition tests on household furniture in the UK and ignition strength tests in the **USA** which showed fewer furniture ignitions with RIP cigarettes (than filter-tipped cigarettes most popular at the time of the study which in turn showed fewer than untipped cigarettes) in the **UK** (Paul 2000 [2++]) and significantly reduced ignition propensity with RIP cigarettes (≤10% of ‘full length burn’ (FLB) compared with >75% FLB for non-RIP cigarettes) in the USA (Seidenberg *et al*. (2011 [2+]). As a result of legislation introduced in November 2011, all cigarettes sold in the EU must be of a reduced ignition construction (European Commission 2011).

Discarded glass

5.25 There is moderate evidence that radiant heating via the ‘burning-glass effect’ is unlikely to be a cause of ignition of northern forest fires in the semi-humid climate of **Germany** (Wittich & Müller 2009 [2+]) and no cases were identified from recent **English** wildfire data held by Natural England and submitted to this review where a specific cause was given (Appendix 2 [2+]).

Ammunition and military training

5.26 There is moderate evidence from recent wildfire data held by Natural England and submitted to this review (Appendix 2 [2+]) that ignitions associated with military training are relatively uncommon and localised in England, with 21 cases identified (6% of the 382 cases where a specific cause was given).

5.27 Wildfire statistics recorded for land in the Ministry of Defence (MOD) estate were submitted to the review for 2019 (to July). These provide moderate evidence of military training as a cause of wildfire with 20 instances (plus four of arson and two cause unknown on MOD land), all relatively small (≤5 ha) and affecting a range of “fuel types”: gorse/bracken (9 instances), grass (9), peat (6, all but one surface only), gorse/bracken/grass (1) and woodland/pine (1) (MOD 2019 [2+]). However, larger fires do occur at times on MOD land, for example at Salisbury Plain and Otterburn Ranges in 2018 (Perry 2019 [2+]).

5.28 There is moderate evidence from a study in the **USA** that bullets can cause ignition of organic matter after impacting a hard surface, particularly those containing steel components (core or jacket) or made of solid copper, though lead core-copper jacketed bullets caused only a single ignition (Finney *et al*. 2016 [2++]). Bullet fragments could exceed 800 °C and were larger for solid copper and steel core/jacketed bullets than for lead core bullets, which facilitates ignition. Fragments cool rapidly but can ignite organic matter, particularly fine material, if very dry and close to the impact site. Peat volumetric moisture content of 3–5%, air temperature of 34 °C to 40 °C and relative humidity of 7 to 16% were necessary to reliably cause ignition in experiments. Peat moisture content of above around 8% did not produce ignition.

Managed burning in the UK

5.29 Managed burning is relatively widely carried out in the UK on *Calluna*- and other dwarf-shrub-dominated heathlands and peatlands, and some other, often associated, habitats including gorse *Ulex* spp. scrub/heath and some grasslands and fens (Thompson *et al*. 1995, Yallop *et al.* 2005, 2006 and Thacker *et al*. 2015; also see para. 9.64 regarding the extent affected). It is principally done in the uplands particularly in spring, especially for game (red grouse *Lagopus lagopus scotica*) and livestock management (Yallop *et al*. 2009 and Glaves *et al*. 2013), though it is also used more locally in the lowlands (Defra 2007) including for habitat management (also see Section 8 on Reducing the impact of wildfires in relation to fuel load management, para. 8.4). Its use has been increasing on heathland and peatland in the uplands of England and Scotland (Yallop *et al*. 2005, Douglas *et al*. 2015 and Thacker *et al*. 2015).

5.30 In England, burning is restricted by the Heather and Grass etc. Burning (England) Regulations 2007[18] and is the subject of a voluntary 'good practice' code (Defra 2007), though adherence to the code is a requirement of agri-environment scheme agreements. The Regulations include a number of requirements and prohibitions, including that there are "… sufficient persons and equipment to control and regulate the burning during the entire period of the operation" and that "… all reasonable precautions [are taken] to prevent injury or damage to any adjacent land, or to any person or thing on that land." Burning is also restricted to a 'burning season' from 1 October to 15 April in the uplands (SDA) and 1 November to 31 March in the lowlands, and to an individual burn size not exceeding 10 ha (Defra 2007). Grouse moor burning is traditionally done in small patches or strips (Hudson & Newborn 1995) with, for example, a median size of 0.25–0.28 ha in Yallop *et al*. (2005), though agricultural burns for livestock tend to be larger (e.g. Defra 2013). Information on reported potential breaches of the Regulations, some of which may result in wildfires, is maintained by Natural England.

5.31 Similar burning, principally for agriculture, especially livestock grazing, is carried out elsewhere in Europe, especially around the Mediterranean, where it is generally referred to as 'traditional' burning or fire use, whereas on the continent 'prescribed burning' tends to be used to refer to modern, generally professional burning, particularly with a fire hazard/fuel load reduction objective (e.g. Lazaro & Montiel 2010). For clarity, this definition has been followed in this review report (para. 1.9 and footnote 3, p 2), with burning mainly for game and agricultural management in the UK here referred to as management or managed burning (although it is widely referred to as prescribed burning in other publications).

5.32 It has been suggested that there is limited information on the frequency of managed burns becoming out of control wildfires in the UK (e.g. Worrall *et al*. 2011 [3+] and Werrity *et al*. 2015 [3+]), though recently more has become available. This includes statistics on wildfire occurrence compiled nationally, regionally and locally, particularly by the FRS (complied nationally in the IRS since 2009, para 4.3) and for some National Parks and Areas of Outstanding Natural Beauty (AONB) (e.g. Appendix 2 [2+]). Together this provides strong evidence that managed fires escaping control cause a proportion of wildfires, particularly in the uplands (de Jong *et al*. 2016 [2++], Luxmoore 2018 [2+], Martin (2018 [2+]), Legg *et al*., 2006 [3+], Worrall *et al*. 2011 [3+], Moors for the Future (2009 [2+]) and Appendix 2 [2+]). This includes strong or moderate supporting evidence from the following national, regional and local studies and data sets across a range of study types:

a. Strong evidence from recent (2002–18) *English* wildfire data held by and submitted to Natural England (Appendix 2 [2+]) which includes 57 cases where managed burns escaping control were identified as the cause of ignition (15% of the 382 ignitions where a specific cause was identified). The percentage was much higher in the uplands (68% c.f. 5% in the lowlands), probably at least in part reflecting the generally much wider use of managed burning in the uplands (para. 5.29–5.30 above) and lower incidence of deliberate and accidental wildfires.

b. Strong evidence from a *Scotland*-wide analysis of FRS records by Luxmoore (2018 [2+]) that reported that 60% of 'primary' wildfires (140 out of a total of 233, 2009/10 to 2014/15) were "potentially caused by muirburn", ranging between 48% and 67% per year and varying geographically by region, with most in Highland region (mean seven per year), but with the highest proportion potentially caused by muirburn in Perth & Kinross (100%, though mean only one per year).

c. Strong evidence from an *English* Peak District study using National Park ranger reports showed that, while the minority, 10 out of 41 fires (24%) with cause identified from 1976 to 2004 were specifically attributed to escaped managed burns, they tended to be much

[18] The Heather and Grass Burning Regulations 2007: http://www.legislation.gov.uk/uksi/2007/2003/contents/made..

larger, resulting in 51% of the area affected by wildfires being due to this cause (Worrall *et al.*, 2011 [3+]), though similar data by area was not available from other studies. Moors for the Future (2009 [2+]) also noted that in the Peak District "[managed] fires used for grouse moor and grazing management sometimes burn out of control, although when well-managed, they can also help to prevent a build-up of fuel load" (though see para. 8.4 regarding use of burning to manage fuel load).

d. Moderate evidence from a questionnaire survey of 41 *Scottish* estates reported by Legg *et al.* (2006 [3+]) which recorded a total of 17 wildfires in 2003, of which nine had been caused by grouse moor muirburn and a further two by farmers burning vegetation for livestock grazing, giving a total of 65% caused by escaped managed fires, similar to the 60% reported by Luxmoore (2018 [2+], para. 5.32b above) from Scottish national FRS statistics. It was estimated that each of the 20 estates included in the survey that conducted muirburn set an average of 215 fires a year, with one estate setting 900–1,000 fires in a season. Thus, it was suggested that most of the fires set for management purposes are closely controlled and that very few escape, though Luxmoore (2018 [2+]) points out that this demonstrates the large scale of muirburn from which just a few escapes may potentially result in significant wildfires.

e. Moderate evidence from a case study on Darwen and Turton Moors (mostly on blanket bog), in the *English* West Pennines, between 1995 and 2017 that, of 22 "main wildfires", one related to escape from a grouse moor strip burn and a further seven were considered likely due to managed burns for livestock grazing getting out of control, especially on *Molinia*-dominated areas (though the latter declined over the more recent period, it was suggested in response to agri-environment agreements with burning plans) (Martin 2018 [2+]). This represents 36% of wildfires resulting from escaped managed burns. Of the remainder, 12 were due to arson by persons unknown (55%) and two were considered either arson or escaped agricultural burns (9%).

f. Moderate evidence from data on wildfire occurrence over 18 years (1998–2015) on *Scottish* National Trust properties covering an upland area of 63,316 ha where no managed burning takes place (Luxmoore 2018 [2+]). Over this time, there were 12 large wildfires covering 1,463 ha or 2% of the upland area (equivalent to 0.1% per year). The largest proportions burnt per individual estate upland area were 19% at Torridon and 17% at Goatfell (equivalent to 1% per year in both cases). It was noted that had there not been a policy of no burning, then the whole moorland area (63,316 ha) might have been burnt over a period of around 18 years compared to the 1,463 ha actually affected by wildfire, though an unknown proportion of the upland area may have been unsuitable for burning.

Arson

5.33 In a review of bushfire arson in **Australia**, Willis (2004) noted that "while there are many different approaches to classifying arson, and different terminology is used by different writers, when taken as a whole the literature suggests the following common motives for arson: revenge, usually against an employer, lover or institution; excitement or relief of boredom; vandalism, often influenced by peer pressure; financial gain, including insurance fraud and for other business purposes; and attention-seeking, including as a 'cry for help' or to gain recognition and 'hero status'."

5.34 As noted earlier (para. 5.6), there is strong evidence from recent English wildfire data (2002–18) held by and submitted to Natural England (Appendix 2 [2+]), that, where a cause of fire was assigned (3,269 fires), the majority of incidents (77%) were classed as deliberate (arson). The percentage considered deliberate was much higher in the lowlands (80%) than the uplands (55%).

5.35 There is strong evidence from an analysis of 55,000 'grassfires' and nearly 550 forest fires in in south Wales (para. 4.3) that wildfires are associated with public access, with over 90% of 'grassfires' recorded within 100 m of a road or public right of way (PROW) and 99% within 500 m of a road or PROW, and with deprivation, with the 20% of most deprived areas in the region nine times more likely to experience wildfires than the 20% least deprived areas (Jollands *et al*. 2011 [2+]).

5.36 There is moderate evidence from a linked investigation of community and stakeholder perceptions of wildfire which revealed low public awareness of wildfires in south Wales, with only 33% believing that there is a wildfire problem across the region and even less (18%) in their local area, though 65% believed that wildfires were deliberately caused (Jollands *et al*. 2011 [2+]) (also see para. 7.6 regarding educational strategies to address fire-starting in south Wales).

5.37 There is moderate evidence from modelling of wildland arson and autoregressive crime function in the **USA** that economic conditions within given areas have an influence on the level and location of criminal wildfire activity and that patterns of such activity could be used to plan law enforcement preventative action (Prestemon & Butry 2005 [2++]). Forest management activity can both reduce and encourage the level of wildland arson activity. Linked to this, there is moderate evidence that arson shows temporal and spatial patterns in response to long- and short-term drivers, with explanatory variables including factors associated with economic conditions and level of law enforcement (Prestemon & Butry 2010 [3+]). Arson was considered predictable over short and long timespans as its rate is heavily influenced by weather, climate, fuels and information on other nearby and recent arson fires.

5.38 There is moderate evidence from a review of socio-economic modelling of fire incidence with an emphasis on urban residential fires in the **USA** that concluded that fire rates are affected by community characteristics, with socioeconomic and environmental factors the primary determinants of fire loss, with fire departments a secondary influence (Jennings 1999 [3+]).

Evidence gaps and research recommendations on wildfire ignition

5.39 Assessment of the available evidence summarised above suggests that the following areas would benefit from further research, monitoring or other investigation:

a. Where possible, standardisation of the range of variables recorded and definitions used, particularly for cause of ignition, between IRS and other wildfire recording schemes to improve compatibility of data nationally.

b. Improved recording of wildfires not attended by the Fire and Rescue Service, and hence not included in the IRS, using new or existing recording systems, for example those maintained by Natural England and the MOD.

c. Extension of the main analyses done so far using the Home Office's national Incident Recording Scheme (IRS) to further explore the occurrence of wildfire in England (and potentially the rest of GB/UK) and factors that may influence this and its severity, extent and impact. Specifically, this should include the timing (e.g., weekly/monthly/seasonally), cause (ideally using agreed definitions/classification), and specific habitat (e.g., using Natural England's Priority Habitat Inventory) and land use types affected.

d. Further exploration, and potentially modelling, of factors associated with the occurrence of wildfires using the IRS and additional data sets held by government (e.g., MOD and Natural England) and other organisations.

e. Wider exploration of the effect of weather events and climate on wildfire occurrence and extent using existing weather and climate, and wildfire data.

f. Review and extension of the potential use of Earth Observation data to improve wildfire mapping and characterisation (e.g., of severity, Schepers *et al*. 2014 and Scottish Natural Heritage 2018), perhaps linked to existing GIS data sets. This could address other recommendations regarding occurrence, severity, extent and impact, particularly those above.

g. Incorporation of socio-economic aspects of wildfires in consideration of monitoring and research on their occurrence, severity, extent and impact, and in wildfire prevention and management/control (reducing impact). This could be done separately or ideally be integrated with biophysical research, but in either case, the findings ought to be interpreted holistically. It should involve engagement with the wildfire community, other stakeholders, land managers and the public.

h. Investigation of the relationship between routine managed burning and prescribed burning (and cutting/mowing and other management with a fuel management objective), and wildfire occurrence, extent, and ideally severity and impact. This should consider the potentially beneficial effect of fuel management and how factors such as the scale, pattern frequency and targeting (in relation to risk factors) affect this, and the effect of burns escaping control resulting in wildfires and the factors that contribute to and cause loss of control. The latter could include consideration of indirect effects such as effects of managed/prescribed burns on vegetation composition (e.g., dominance of potentially flammable vegetation types) and water table (lowering).

i. Extension of recording/mapping of managed/prescribed burning in England potentially using Earth Observation, particularly in the uplands, in part to contribute towards investigation of the relationship with wildfire occurrence.

j. Similar to (h) above and potentially linked to restoration below, a broader investigation of the effects of wider management interventions, e.g., grazing, scrub and bracken management, and drainage, on wildfire occurrence, severity, extent and impact.

k. Collation nationally of details on any prosecutions that arise as a result of wildfires (for arson and if possible for breaches of the Heather and Grass Burning Regulations) to allow identification of common issues etc.

l. In reviewing factors associated with wildfire severity and impact, potential impact should also be considered. This includes inputs (e.g., guidance and effectiveness) to risk registers, and tools developed for wildfire management planning including risk assessment, scoring and mapping and fuel mapping.

6 Wildfire behaviour and severity

6.1 The full text of question 3 is:

What factors influence fire behaviour and severity?

Introduction

6.2 This question has been interpreted relatively widely here in relation to factors contributing to fire behaviour ("the manner in which fuel ignites, flame develops and fire spreads", including intensity) and severity (loss/consumption of, and immediate post-burn effect on, above and below ground fuels/vegetation) (Keeley 2009 and Davies 2013; also see Appendix 10). Though not strictly part of fire behaviour or severity, the size/extent of individual wildfires is also covered to some extent here, though evidence on this and the total extent of wildfires in and across years is also dealt with under risk and occurrence (Section 4). Hot metal particles and embers or firebrands that may be important in terms of wildfire ignition and spread are dealt with under the previous section on ignition (paras. 5.18–5.20).

6.3 There is some overlap with ignition, but ignition sources are mainly dealt with in the previous section (5). The wider, including longer-term, effects and impacts of wildfire, classed by Prestemon *et al*. (2013 [3+]) as: (1) civilian and firefighter health and safety, (2) damage to resources and structures and (3) future ecological conditions, are beyond the scope of this evidence review (para. 1.15), though they are briefly summarised in the Introduction (paras. 1.9–1.10 and 1.15).

6.4 Murgatroyd (2002 [3+]) in a Forestry Commission Technical Note on *Forest and moorland fire suppression* describes fire characteristics in a UK setting. This notes that *Calluna* and *Molinia* fuels are classed as 'fine fuels' and that dead material in these fuels dries out rapidly in all seasons and they also have low fuel moisture content when dormant in winter/spring. Fires in these fuel types often develop sufficient intensity to be classed as 'high', or even 'very high' in stronger wind conditions (but not extreme), using the Australian Fire Authorities Council rating system.

Summary of evidence on fire behaviour and severity

General fire behaviour and severity

6.5 There is moderate evidence that fuel load and vegetation structure, and hence vegetation and habitat type (though most evidence relates to *Calluna*-dominated vegetation), are critical factors in fire behaviour in UK heathlands and peatlands, particularly in fireline intensity (heat output per unit length of fire front) and rate of spread, although residence time and depth of penetration of lethal temperatures into the soil are also important in determining severity, but are less well understood (Davies 2005 [+], Davies *et al*. 2010 [2+], Davies & Legg 2011 [2+] and Legg & Davies 2009 [3+]).

6.6 There is also moderate evidence that fire behaviour in *Calluna*-dominated heathland and peatland vegetation in the UK is determined by wind speed, though this interacts with vegetation structure and fuel load which is influenced by *Calluna* growth phase, though this interaction may vary between habitats and time of year (Davies *et al*. 2009 [2+] and Davies *et al*. 2008 [3+]).

6.7 There is moderate evidence that drought or water deficit in *Calluna* provides conditions for an increased rate of spread and intensity of fire in the UK (Grau 2016 [2++], Grau *et al*. 2016. [2++], Davies & Legg 2011 [2+] and Davies & Legg, 2016 [+]) and that physiological drought may be caused by cold, clear weather and frozen ground, and winter cuticle damage, which can reduce the fuel moisture content of live biomass and create the potential for ignition, increase the rate of spread and extreme fire behaviour, particularly in spring in the UK (Davies *et al*. 2010 [2++], Grau-Andrés 2016 [2++], Grau *et al*. 2016 [2++], Davies 2005 [2+], Davies & Legg, 2011 [2+] and Davies & Legg, 2016 [2+]).

6.8 There is moderate evidence that critical differences in burn severity and fuel consumption are linked to the flammability of ground fuel layers including in bryophytes and litter in UK heathland and peatland (Davies *et al*. 2016 [2+] and Davies & Legg, 2011 [2+]).

6.9 Most of the above evidence is based on *Calluna*-dominated UK heaths and bogs and there appears to be limited evidence on fire behaviour and severity from other UK vegetation types which are widespread in the uplands and lowlands and are affected by wildfires (paras. 1.18–1.20), including other dwarf-shrub and gorse *Ulex* spp. dominated heaths and bogs, graminoid-dominated heaths, bogs, fens and grasslands, especially by *Molinia* and cottongrasses *Eriophorum* spp., and sometimes deergrass *Trichophorum germanicum*, and less-modified, *Sphagnum* bog-moss-dominated bogs and fens, and other bryophyte-dominated vegetation.

6.10 Some similar, consistent evidence is available from non-UK, open habitats, e.g., moderate evidence that live-fuel moisture content, shrub-layer density, presence of litter and wind, and the amount and continuity of the dead elevated fuel, all influence the sustainability of fire spread in **Australian** shrubland (Plucinski *et al*. 2010 [2++]).

Fire temperatures

6.11 Findings from a range of studies investigating above- and below-ground fire temperatures are briefly described in Appendix 9. *Calluna*-dominated dry heath and blanket bog habitats have been the subject of a number of studies that have reported maximum fire temperatures in the canopy in the range 485–993 °C, with mean maximum temperatures up to 670 °C. There appears to be considerable variation in recorded temperatures within and between studies, with soil temperatures and fires at the base of vegetation typically in the range 7–87 °C, but up to a maximum of 982 °C. A similar range of temperatures has been reported for other habitats, although in forests surface fire temperatures up 1005 °C have been recorded.

Vegetation and habitat types

6.12 There is moderate evidence that fire severity (including ground fuel consumption, ground heating and changes in post-fire soil thermal dynamics) vary by habitat/vegetation type in the UK (Hudspith *et al*. 2014, Grau *et al*. 2016 and Grau-Andrés *et al*. 2018 [all 2++]) and elsewhere, e.g., **Canada** (Camill *et al*. 2009 [2++]). This includes moderate evidence that in the UK, *Calluna*, dry heath and tree dominated sites suffer more severe burning than bog, flushes/fens and bog woodland (Hudspith *et al*. 2014 [2++], Grau *et al*. 2016 [2++] and Grau-Andrés *et al*. 2018 [2++]) and that fires on **Canadian** peatlands became more severe following a shift from moderate-rich fen to forested bogs as a result of climate change (Camill *et al*. 2009 [2++]).

6.13 Moderate evidence indicates that fire spread in **Spanish** shrubland is facilitated by land use/cover types with a high fuel load and homogenous terrain (Loepfe *et al*. 2010 [2+]), and by low fuel moisture, with the fire intensity of mature *Ulex* shrub as high as the maximum intensity recommended for prescribed fires (Baeza *et al.* 2002 [2+]).

Evidence gaps and research recommendations on fire behaviour and severity

6.14 Assessment of the available evidence summarised above suggests that the following areas would benefit from further research, monitoring or other investigation:

a. Extension of research into fire behaviour, fuel moisture dynamics, severity, extent and impact, especially in non-*Calluna*-dominated vegetation, and across habitat transitions, potentially including to forestry/woodland and the urban-fringe, in part to input to development of a full FDRS.

b. In reviewing factors associated with wildfire severity and impact, potential impact should also be considered. This includes inputs (e.g., guidance and effectiveness) to risk registers, and tools developed for wildfire management planning including risk assessment, scoring and mapping and fuel mapping.

c. Development of an approach to recording burn severity using a simple on-the-ground method of assessment, potentially for use in wildfire recording schemes, and/or based on Earth Observation.

7 Wildfire prevention

7.1 The full text of question 4 is:

What are the most effective measures for preventing wildfire?

7.2 In addition, the following related questions 5 to 7 which address particular aspects of prevention are dealt with in this section:

What are the characteristics of effective firebreaks?

How effective is the Met Office Fire Severity Index in predicting potential fire severity?

How effective is 'fire watching' in preventing and reducing the impact of wildfire?

Introduction

7.3 Prestemon *et al.* (2013 [3+]) noted that "there has been scant research published in the refereed literature on the effects of wildfire prevention efforts. This is in spite of widespread acceptance that prevention efforts are worthwhile." In its "Wildfire Prevention Strategies" publication, the [**US**] National Wildfire Coordinating Group (1998) defines wildfire prevention as consisting of "administrative, education, enforcement, and engineering activities". The last three are included in Prestemon *et al*.'s (2013 [3+]) conceptual model (given in modified form in Figure 1) with administration assumed to operate at larger spatial and temporal scales, though it is included here with the other prevention activities.

7.4 For clarity, in addition to the general subject, some specific aspects of prevention considered under separate questions are brought together in this section as sub-sections on: firebreaks, the Met Office Fire Severity Index and 'fire watching' (see Figure 1), the last of which can also be regarded as a contribution to reducing impact (Section 8).

Summary of evidence on wildfire prevention in general

Education, and cultural and community attitudes

7.5 There is limited information on the implementation and particularly effectiveness of education and training strategies in relation to wildfire prevention in the UK, though a number of such community partnership projects have recently been established on the urban-rural fringe especially adjacent to lowland heathlands. These include the 'Bernie Project'[19] with Forestry Commission Wales and a number of other Forestry Commission initiatives including in the New Forest, 'Flames aren't games' with Staffordshire FRS[20] and the FireWise Communities Project which so far has groups in Dorset[21] and Surrey. This issue is also dealt with under a number of wider partnership projects such as the Dorset Urban Heaths Partnership[22].

7.6 There is moderate evidence that proactive and reactive education measures used by the Forestry Commission Wales and partners in south Wales can reduce the incidence of wildfire arson (Jollands *et al*. 2011 [2+]). This included community projects such as the 'Bernie Project' in Tonypandy in Mid-Rhondda, which used 'social marketing' techniques to target thirteen to sixteen year-olds over a six-week period which resulted in a relative decrease of 46% (compared with a nearby control) in the number of vegetation wildfires over the period of the intervention which continued for some time after the intervention ended.

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[19] The 'Bernie Project': http://your.caerphilly.gov.uk/saferccb/fire-safety/project-bernie.

[20] 'Flames aren't games': https://www.staffordshirefire.gov.uk/your-safety/campaigns/flames-arent-games/.

[21] Firewise-UK Community Project, Dorset: https://www.dwfire.org.uk/news/firewise-uk-project-launched-in-dorset/.

[22] Urban Heaths Partnership: https://www.dorsetcouncil.gov.uk/countryside-coast-parks/dorset-heaths/protecting-and-managing-the-heaths.aspx.

7.7 There is moderate evidence from elsewhere, particularly **North America** and the **Mediterranean**, that cultural shifts, such as greater awareness of wildfire issues, and the development of community experience and a common vision through education and public participation, may reduce the incidence of wildfire ignitions and, through consensus, lead to the acceptance of the need for actions to reduce the incidence of human-induced fires (Prestemon *et al*. 2010 [3++], Carreiras *et al*. 2014 [3-]), McCaffrey (2004 [3-], Monroe *et al*. (2013 [3-]) and Schauble (2009 [4-]). This includes:

a. Strong evidence that wildfire prevention education efforts in the **USA** have a significant effect in reducing the numbers of wildfires ignited by debris burning, campfire escapes, smoking and children, with the reduction of wildfire damage producing marginal benefits exceeding marginal costs state-wide by an average 35-fold (Prestemon *et al*. 2010 [2++]). The benefits exceeded costs in 'fire management regions' by 10- to 99-fold depending upon assumptions about how wildfire prevention education spending is allocated.

b. Moderate evidence that solutions for dealing with forest wildfire in **Portugal** and **Spain** stem from community experience and vision. Public participation can be of utmost importance for the development of a common vision and the definition of actions that are accepted by consensus (Carreiras *et al*. 2014 [3-]).

c. Moderate evidence from a Bayesian Network simulation model developed for cost-effective fuel treatment solutions aimed at reducing wildfire risk to housing at the urban interface in south-eastern **Australia** indicated that community education had only a limited effect on the extent to which residents prepared their properties, though increasing expenditure on wildfire suppression resources resulted in a greater reduction in risk of loss of housing than preparedness (Penman *et al*. 2014, 2015 [both 2+]).

Habitat restoration

7.8 Restoration of moorland habitats, in particular peatlands, including through rewetting and treatments to reduce cover of 'over-dominant' species, has been recommended to reduce risk of, and increase resilience to, wildfire in the UK (e.g. McMorrow & Lindley 2006 [2+] and Aylen *et al*. 2007 [3+]), as well as for wider benefits, and there is moderate evidence that the severity and perhaps incidence of wildfires may be reduced when wetter conditions, in particular high water tables, are maintained or restored (Grau-Andrés 2016 [2++], Grau *et al*. 2016 [2++] and Aylen *et al*. 2007 [3+]).

7.9 There is similar moderate evidence that fire effects, including ground fuel consumption, ground heating and changes in post-fire soil thermal dynamics, were stronger on a UK dry heath compared to a raised bog (Grau 2016 [2++] and Grau *et al*. 2016, [2++]), which is consistent with the likely benefits of rewetting modified bog and fen habitats.

Wildfire risk assessment and management planning

7.10 Wildfire management planning is accepted good practice and, for example, with risk assessment, is a requirement under Countryside Stewardship agri-environment agreements with lowland heathland and moorland options. In part to address this requirement, the Uplands Management Group has recently produced guidance on *Moorland wildfire risk assessment and management planning* on behalf of Defra (Uplands Management Group 2019 and Appendix 12) based on Forestry Commission guidance (Forestry Commission 2014, para. 7.11 below). This covers Wildfire Risk Assessment (WRA) including a Wildfire Risk Scoresheet (WRS), Wildfire Response Plans (WRP) and Wildfire Management Plans (WMP).

7.11 The Forestry Commission's guide on *Building resilience into forest management planning* provides guidance on managing vegetation and fuels for land managers in forestry and associated open habitats which includes vegetation management (forestry operations and mechanical cutting), grazing and burning using a matrix linked to Wildfire Management Zones to ensure a proportionate approach a both site and landscape scales (Forestry Commission 2014; also see guidance in Appendix 7).

Evidence gaps and research recommendations on wildfire prevention in general

7.12 Assessment of the available evidence summarised above suggests that the following areas would benefit from further research, monitoring or other investigation:

a. Incorporation of socio-economic aspects of wildfires in consideration of monitoring and research on their occurrence, severity, extent and impact, and in wildfire prevention and management/control (reducing impact). This could be done separately or ideally be integrated with biophysical research, but in either case, the findings ought to be interpreted holistically. It should involve engagement with the wildfire community, other stakeholders, land managers and the public.

b. In reviewing factors associated with wildfire severity and impact, potential impact should also be considered. This includes inputs (e.g., guidance and effectiveness) to risk registers, and tools developed for wildfire management planning including risk assessment, scoring and mapping and fuel mapping.

c. Exploration of the effectiveness of Wildfire Risk and Fuel Maps and associated guidance, and the role they may have in wildfire prevention and control/management.

d. Investigation of the effectiveness of access closure and restrictions, including Access Management Plans, and potentially management restrictions, on wildfire occurrence, severity, extent and impact.

e. Research into the influence of sward composition and structure on the occurrence, severity, extent and impact of wildfire.

f. Investigation of the effect of peatland and other habitat restoration on wildfire occurrence, severity, extent and impact, and its effect on habitat resilience (linked to (e) above).

Firebreaks

7.13 The full text of question 5 is:

What are the characteristics of effective firebreaks?

Introduction

7.14 Firebreaks are natural or man-made generally linear gaps in vegetation or other combustible material that aim to prevent or reduce the spread of surface fires such as heavily grazed, cut, mown or burnt areas (Forestry Commission 2014). Similar fuel breaks are gaps in vegetation where litter and organic materials are also removed to expose mineral soils such as eroded areas and rocky outcrops, roads, tracks, banks and ploughed, scraped or bulldozed lines. Both require regular maintenance to remain effective as control measures and can aid access and the distribution of fire control equipment during a wildfire incident. Fire belts are strips of woodland composed of fire-resistant (usually broad-leaved) species, which help maintain a 'clean' forest floor and prevent or reduce the spread of surface and crown fires.

7.15 The Forestry Commission’s (2014) guide on *Building resilience into forest management planning* provides guidance on designing fire and other breaks, including location (e.g. at critical points where they could be used to prevent extreme fire behaviour such as at the bottom or ridge line of a slope) and size, which “will be dependent on fire risk and the intensity at which a fire is likely to burn”. The guidance recommends that “in general, the following principles should be applied:

a. The taller the vegetation, the wider a fire or fuel break should be.

b. Firebreaks should be wider where high-risk vegetation [such as gorse *Ulex* spp.] is adjacent to, or within the vicinity of, assets and infrastructure. A ratio of 3:1 is a recommended minimum.

c. Fire and fuel breaks should be accessible to a fire appliance (measuring 3 m wide by 3.5 m high) where ground conditions allow.

d. Fire belts should be at least 20 m wide and wider where assets are at risk."

A Forestry Commission Technical Note on *Forest and moorland fire suppression* notes that experience has shown that to be effective a fire break is required to be at least 2.5 times flame height (expected flame length) which is normally 6 m to 10 m wide to be reliable under all conditions (Murgatroyd 2002 [3+]).

Summary of evidence on the effectiveness of firebreaks

7.16 Though detailed guidance on the location and design of firebreaks is available, particularly from the Forestry Commission (2014, outlined above), and their use is widely recommended, for example, by Shaw *et al*. (1996 [3+]) who noted that advice from the Peak District Moorland Management Project recommended that moorland "should be managed by rotational burning in winter, or cutting, to create irregular fire breaks close to public access paths which would help limit the spread of fires in summer", limited evidence was identified specifically on the effectiveness of firebreaks for reducing the occurrence and spread of wildfires in the UK (though also see Section 8 in relation to their use in fire suppression, e.g., para. 8.11).

7.17 Operational proactive strategies used by Forestry Commission Wales include 'designing in' firebreaks in forest planning that can help tackle the spread of large-scale forest fires, though this has apparently been given less emphasis recently within the planning process and there appears to be little information available on its effectiveness (Jollands *et al*. 2011 [2+]).

7.18 **Away from the UK**, firebreaks are more widely used and there is moderate evidence that they can be effective in certain situations and conditions, with vegetation type and structure/height, weather conditions, especially wind speed, and season being important factors, though effectiveness also depends on firebreak characteristics, especially width, and they tend to become less effective or ineffective in more extreme conditions (Price *et al*. 2007 [1++], Suffling *et al*. 2008 [2+], Cheney & Sullivan 1997 [3+] and Luke & McArthur 1977 [3-]). This includes moderate evidence from the following examples:

a. A study in a savanna woodland region of northern **Australia** indicated that 'permanent' firebreaks (cliffs, streams, tracks and roads) are not certain instruments for fire management: cliffs were more effective than streams at stopping fires which were more effective than roads (Price *et al*. 2007 [1++]). Larger streams were more effective than smaller ones with the largest stopping 75% of early dry season fires, but no firebreak types had a more than a 50% likelihood of stopping a late dry-season fire.

b. A review of grassfires in **Australia** by Cheney & Sullivan (1997 [3+]) indicated that firebreaks were very effective in grassy fuels providing a fire is not spotting; a 10 m firebreak gave a 99% chance of holding a 10 MW/m fire, i.e. a fire in a 4 t/ha fuel travelling at 5 km/h. The same firebreak will hold faster-spreading fires in lighter fuels, but once the wind speed exceeds 25 km/h, burning material will be blown along the ground and even quite wide breaks will be ineffective. Firebreaks were considered much less effective when grasses contain large seed heads that can spot ahead of the fire or when there are trees nearby. Under strong winds, typical of days of extreme fire danger, firebreaks more than 40 m wide may be ineffective in stopping a head fire. Breaks parallel to the prevailing wind direction may hold the flank fire (see Appendix 10) and assist with suppression. Bare earth firebreaks were considered essential around any burning-off operation. Under extreme conditions, a fire with flames only a few centimetres high can spread across eaten-out paddocks.

c. Luke & McArthur's (1977 [3-]) book includes a wide range of information on bushfires in **Australia** including on firebreaks. If ignition is solely by radiation or flame contact, firebreaks can be 2–4 times the greatest fire length, but a fast-spreading grass fire exposed to strong winds might require a minimum break of 30 m. In treeless grasslands, spotting distances seldom exceed 100 m, whereas in forests they can be a few metres or 20 km depending on the fuel and weather conditions. Locating and assessing the value of natural firebreaks is the starting point for firebreak planning. Fire-trails on farms are usually 2–3 m wide, i.e. just wide enough for vehicles. If a wider firebreak is needed the usual procedure is to burn between two ploughed or graded lines or to use a track for one edge while controlling the other edge of the fire with water. Narrow firebreaks may not stop fires once they have assumed major proportions. Tracks are generally most effective as firebreaks in locations where fire behaviour is likely to be least violent. Valley bottoms are often acceptable but tops of ridges generally provide better facilities for maintenance and is a suitable place for dealing with fires moving rapidly upslope if adjoining fuels have been reduced. In the 1930s, firebreaks were 40 metres wide. Removal of surface litter is not prescribed as it may lead to excessive scorch and erosion of the bare surface.

Evidence gaps and research recommendations on fire and fuel breaks and fire belts

7.19 Assessment of the available evidence summarised above suggests that the following areas would benefit from further research, monitoring or other investigation:

a. In reviewing factors associated with wildfire severity and impact, potential impact should also be considered. This includes inputs (e.g., guidance and effectiveness) to risk registers, and tools developed for wildfire management planning including risk assessment, scoring and mapping and fuel mapping.

b. Further research on the design and effectiveness of fire and fuel breaks, and fire suppression in open habitats (and forestry).

The Met Office Fire Severity Index and closing and managing access

7.20 The full text of question 6 is:

How effective is the Met Office Fire Severity Index in predicting potential fire severity?

The use of the MOFSI to close open access land and managing access more generally are also covered in this sub-section.

Introduction

7.21 The Met Office Fire Severity Index (MOFSI, Met Office 2003) model has been available since 2004 covering England and Wales. It is based on the Fire Weather Index (FWI) component of the Canadian Forest Fire Danger Rating System (CF FDRS, Van Wagner 1987) adapted to represent UK conditions. It provides daily operational mapping of potential fire severity across England and Wales using a simple thresholding of the FWI. This takes into account simulated moisture conditions at various levels through the soil and incorporates the following weather elements: temperature, relative humidity, wind speed and rainfall, to quantify the likely severity of potential fire (Met Office 2003). It provides information on a daily basis and for five days ahead on a 10-km square grid in terms of a 1 to 5 rating[23] with Level 5 representing ‘exceptional’ conditions when, *if a fire occurs*, it is likely to be extremely difficult to control. It does not provide an assessment of the risk of wildfire actually occurring.

7.22 Natural England have carried out a review of the operation of the MOFSI which was limited in scope to internal processes and communications, although it included commissioning the Met Office to review of the performance of the MOFSI in England and Wales during summer 2018 as a peak wildfire year including a number of large, severe wildfires that generated national publicity (Perry 2019 [2+]; also see Appendices 2 and 8). This involved: (1) a comparison of outputs from the operational version of MOFSI (which is driven by gridded data from numerical weather prediction models), with an equivalent model driven by observations from seven weather stations; and (2) a review of levels of MOFSI indices in relation to the location

[23] Available online at: https://www.metoffice.gov.uk/public/weather/fire-severity-index/.

and timing of six notable wildfire incidents. Together these studies broadly confirmed that the model "behaved as expected" (see para. 7.30). The Met Office review also put the 2018 wildfire season into context by considering how extreme the year was in comparison with previous years back to 2014 using MOFSI outputs and a satellite-derived assessment of area burnt (see para. 4.18c). The findings of these reviews fed into the wider Defra upland peatland wildfire review (para. 2.4).

The CROW Act and closure of open access land

7.23 The Countryside and Rights of Way (CROW) Act 2000 allows for open access land to be closed or access restricted on grounds of land management, public safety, fire prevention and nature conservation. Some of these restrictions take place automatically: for instance dogs must be kept on a lead between 1 March and 31 July and in the vicinity of livestock at all times. Landowners have the discretion to close land for up to 28 days a year for any reason, and additionally for six weeks a year for lambing and to exclude dogs on grouse moors. However, for many restrictions the landowner must apply to the relevant authority under the Act. The relevant authority is the National Park Authority for land within a National Park, the Forestry Commission for dedicated woodland and Natural England for all other open access land in England and for all land in the coastal margin of the England Coast Path.

7.24 Open access land is land that was mapped as 'mountain, moor, heath or down' and/or Registered Common Land under the Countryside and Rights of Way Act 2000. This covers a total of 865,119 ha. In addition, other land has been dedicated as open access by the Forestry Commission (most of its freehold land), Natural England (the majority of NNRs) and some private landowners, covering a further 168,469 ha, and giving a total of 1,033,588 ha.

7.25 The MOFSI provides a trigger for fire prevention restrictions on open access land mapped under the CROW Act (2000) which aim to minimise accidental fires on access land vulnerable to wildfires by suspending open access rights when conditions become 'exceptional' (MOFSI level 5). 'Outline directions' may be put in place by responsible bodies, or be applied for, which enable restrictions to be activated immediately if conditions become 'exceptional'. The bar for the 'exceptional' threshold on the MOFSI is purposely set high to reflect Parliament's intention that CROW land should only be restricted during conditions beyond what might normally be expected for the time of year, and to ensure that land was not closed on days of typical, seasonal hot weather. The restriction remains in place after the MOFSI has dropped below level 5 for a number of days: either below level 3 for three days or below level 5 for five days, to ensure that 'exceptional' conditions have passed.

7.26 Potential closure under the CROW Act only applies to open access land and hence not to public rights of way or land under other access agreements. Thus, public rights of way that often cross open access land are likely to limit the effectiveness of closures under the CROW Act.

Daily Hazard Assessment

7.27 A Natural Hazards Partnership (NHP)[24] was established in 2011 to provide coordinated on information, research and analysis on natural hazards for the development of more effective policies, communications and services for civil contingencies, governments and the emergency responder community across the UK (Hemingway & Gunawan 2018). As part of this a Daily Hazard Assessment (DHA) provides an 'at a glance' mapped overview of 21 potential natural hazards and health implications that could affect the UK over the following five days. Wildfire is one of 12 hazards included in a colour-coded Hazard Matrix that informs the DHA:

- Green: elevated wildfire conditions not forecast (low risk of wildfires).
- Yellow: elevated wildfire conditions (likelihood of manageable wildfires) forecast.

[24] Natural Hazards Partnership: www.naturalhazardspartnership.org.uk.

- Amber: severe wildfire conditions (likelihood of difficult to control wildfires) forecast.
- Red: high confidence of severely disruptive wildfire(s).

7.28 The DHA wildfire hazard is informed by the sub-indices of the MOFSI. Whilst the MOFSI and DHA use the same meteorological model, the assessment outputs are for different purposes and are currently presented in very different ways, though there may be scope to review whether the two systems can be aligned in a way that would fulfil the need to determine when CROW Act restrictions should be in place and also provide an assessment on the likely occurrence and severity of wildfires that can be used by government and emergency responders.

Summary of evidence on and relevant to the MOFSI

Prediction of extreme fire weather conditions

7.29 There is moderate evidence that the MOFSI and the Canadian Fire Weather Index (FWI) on which it is based, in particular the Fuel Moisture Code (FMC) and Initial Spread Index (ISI) components, successfully predict extreme fire weather conditions in the UK which may give rise to particularly severe wildfires should they occur (Davies & Legg 2016 [2+] and Perry 2019 [2+]). But that it is less successful in predicting when fires actually occur, especially in the recorded spring peak period (para. 4.15) when ignition can occur as a result of drought stress of *Calluna* (de Jong *et al*. 2016 [2++], Davies & Legg 2011 [2+] and Krivstov & Legg 2011 [2+]), though this is not an objective of the current MOFSI.

7.30 There is moderate evidence from a Met Office review on the performance of the MOFSI in 2018 (Perry 2019 [2+]), a peak wildfire year in England and Wales that:

a. There was a strong correlation in the FWI derived from the operational MOFSI model and an equivalent observation-driven model for each of seven weather stations selected to represent a range of conditions across England and Wales. In the large majority of cases the occurrence of severe fire weather was well predicted by the forecast model, though a small negative bias in the operational FWI compared to the version driven by site observations was identified at some sites, though this had no impact on Level 5 ('exceptional') being reached at any of the sites.

b. Levels of MOFSI indices in relation to the location and timing of six notable wildfire incidents[25] in 2018 showed that "elevated [but not 'exceptional'] fire weather conditions contributed to the severity of the incidents"; on the day of the fires, the MOFSI was at Level 4 (very high) at one site, Level 3 (high) at three sites and Level 2 (moderate) at one. At a further three sites the MOFSI increased to Level 4, leading to the fires spreading or further fires starting, so that it took several weeks before the fires were brought under control, and at two sites the MOFSI peaked at Level 3 during the incidents. The hot, dry conditions led to a steadily increasing Build-Up Index (BUI) from mid-June to mid-July and particularly severe conditions occurred on windier days when the Initial Spread Index (ISI) was elevated. Though Level 5 was not reached at any of the major event locations, the duration of high FSI values is likely to have contributed to the severity of the wildfire conditions experienced.

c. High levels of fire weather severity (MOFSI Levels 3 and 4) were widespread across England and Wales during the summer of 2018 and were sustained over a duration of several weeks due to a period of hot, dry weather, though MOFSI Level 5 was reached on only four days in 2018, over small areas of East Anglia and south-east England. Lower relative humidity or stronger winds would have been required to trigger 'exceptional' conditions more widely. (Also, see para. 4.18c for comparison of 2018 with earlier years.)

[25] Wildfire causes at the six sites were: two due to live firing on MOD ranges, two probably arson and the other two uncertain.

Potential refinements and developments

7.31 There is interest in refining the MOFSI/DHA and/or developing a wider Fire Danger Rating System (FDRS) including, for example, an ongoing project at the James Hutton Institute to develop a FDRS for Scotland[26], a recent NERC highlight topic wildfire proposal call[27] and a Forestry Commission briefing note on *Next steps for Wildfire Danger Assessment in the UK* (Tsakiridou *et al*. 2018) which summarised stakeholder views on the need for the development of a fire danger assessment tool, options and alternative paths for implementation, and the associated scale of costs and risks. The studies summarised below provide further moderate and strong evidence that there is scope to refine elements of the FWI to better reflect vegetation types and key species, and conditions in the UK and/or potentially to input to the development of a UK FDRS:

a. There is moderate evidence that the fuel moisture indices do not relate strongly to observed changes in live or dead *Calluna* fuel moisture (Davies & Legg 2011 [2+]), though further research on fuel moisture dynamics may provide substantial improvements to the fuel Moisture Code and Initial Spread Index for UK conditions and habitats (Davies & Legg 2016 [2+]).

b. There is moderate evidence that the moisture status of ground fuel layers is a critical control on burn severity in peatlands which suggests that certain components of the FWI System (Duff Moisture Content, Drought Code and Build-up Index) may be useful in forecasting potential fire severity (Davies *et al*. 2016 [2+]).

c. There is strong evidence that an alternative percentile-based calibration of FWI components optimised for UK conditions offers significant advantages for classifying UK fire danger which could usefully contribute to future development of MOFSI or a new FDRS (de Jong *et al*. 2016 [2++]).

d. There is moderate evidence that an alternative model which calculates a shrub fire index (SFI) more accurately predicts the prevalence of fires in spring in the UK uplands and the secondary peak in the summer, and could therefore contribute to the future development of a fire prediction system designed specifically for British conditions (Krivstov & Legg 2011 [2+]), though this is not an objective of the current MOFSI.

e. Studies of predictions based on the Fire Weather Index and other fire-risk/danger models and variables, e.g., in forested regions of **Spain/Portugal** and **Canada** provide moderate evidence of variation in relative importance of different factors between sites and regions suggesting that enhancements can be made to improve the applicability of such models for conditions in other countries or regions including the UK (Beverly & Wotton 2007 [2++], Carvalho *et al*. 2008 [2++], Bedia *et al*. 2012 [2++] and Mestre & Manta 2014 [2+]).

Use to close access and potentially other actions

7.32 No evidence was identified on the effectiveness of closing or managing access at times of ‘exceptional’ or high risk in the UK in terms of reducing wildfire occurrence, though open access land can be closed under the CROW Act (paras. 7.23–7.26). From time to time, the ‘exceptional’ threshold level of the MOFSI is met, but this does not necessarily overlap with areas of CROW access land identified as vulnerable to wildfire where 'outline directions’ may be in place. The last time that fire prevention exclusions were activated on CROW access land was during May 2011, when 32 fire prevention restrictions were activated in the Peak District National Park, Yorkshire Dales National Park, Lancashire, North Yorkshire, Calderdale, Rochdale, Barnsley, Derbyshire, Shropshire (Stiperstones) and West Sussex, covering a total area of just over 112,000 ha. There is potential for the MOFSI level ratings (or

[26] Scottish FDRS: https://www.hutton.ac.uk/research/projects/scottish-fire-danger-rating-system-sfdrs.
[27] NERC wildfire highlight topic: https://nerc.ukri.org/research/funded/programmes/highlight-topics/news/ao-round5/.

a new FDRS) to be used to target and trigger other voluntary interventions on open access, and potentially other, land.

Evidence gaps and research recommendations on and relevant to the MOFSI

7.33 Assessment of the available evidence summarised above suggests that the following areas would benefit from further research, monitoring or other investigation:

a. Incorporation of socio-economic aspects of wildfires in consideration of monitoring and research on their occurrence, severity, extent and impact, and in wildfire prevention and management/control (reducing impact). This could be done separately or ideally be integrated with biophysical research, but in either case, the findings ought to be interpreted holistically. It should involve engagement with the wildfire community, other stakeholders, land managers and the public.

b. Extension of research into fire behaviour, fuel moisture dynamics, severity, extent and impact, especially in non-*Calluna*-dominated vegetation, and across habitat transitions, potentially including to forestry/woodland and the urban-fringe, in part to input to future development of a full FDRS.

c. In reviewing factors associated with wildfire severity and impact, potential impact should also be considered. This includes inputs (e.g., guidance and effectiveness) to risk registers, and tools developed for wildfire management planning including risk assessment, scoring and mapping and fuel mapping.

d. An investigation with the Met Office to consider the technical feasibility of aligning the wildfire component of the Daily Hazard Assessment with the Fire Severity Index and the potential for the DHA to provide a trigger for ‘exceptional’ conditions instead of the MOFSI.

e. Further investigation of the development of a UK Fire Danger Rating System, including reviewing implementation, engagement/communication and management, and how best to communicate risk warnings to stakeholders, land managers and the public.

f. An investigation of the effectiveness of access closure and restrictions, including Access Management Plans, and potentially management restrictions, on wildfire occurrence, severity, extent and impact.

Fire watching

7.34 The full text of question 7 is:

How effective is ‘fire watching’ in preventing and reducing the impact of wildfire?

Introduction

7.35 ‘Fire watching’, involves a person or ‘fire lookout’ whose role is to watch and search for evidence of wildfire outbreaks from a good vantage point, sometimes, particularly in extensive wilderness areas (e.g. in North America), from a fire or lookout tower, and to raise an alarm to allow suppression or other responses to be undertaken. Automated Early Warning Systems (EWS) are also covered in this section under this question. Fire watching is here treated as a component of wildfire prevention, though it can also be regarded as a contribution to reducing impact (Section 8) through enabling an early response to wildfire outbreaks.

Summary of evidence on fire watching

7.36 Although fire watching has been advocated for some time for use in the UK, particularly at wildfire ‘hot spots’ in the Peak District (e.g. McMorrow & Lindley 2006 [2+], Albertson *et al*. 2010 [2+] and Aylen *et al*. 2007 [3+]), little specific evidence was identified from the UK on its use and effectiveness in preventing, or reducing the impact of, wildfires.

7.37 Limited evidence was identified on fire watching schemes or networks having been established in the UK, though Northumberland National Park was the first UK location to adopt an alarm-based Early Warning System (EWS) in 2013 using an infrared camera system designed to quickly detect wildfire ignitions (Edgeley & Paveglio 2016 [3+]). In addition, a small local community fire watching group recently established at Dovestone on the Peak District fringe generated local publicity on BBC News (also see paras. 7.5–7.6 on FireWise and other urban heath community initiatives). Fire watching and EWS are widely used elsewhere particularly in remote and forested areas where it is important to initiate a rapid response (e.g., see reviews on EWS by Edgeley & Paveglio 2016 [3+] and Forest Fire Detection techniques by Alkhatib 2014).

7.38 There is, however, moderate evidence from the Peak District that resources and interventions that support a rapid, reliable and effective response to a wildfire including fire watching, and improved vehicle access and provision of emergency ponds, may show a high return on investment in terms of fire rescue resources saved, even if dedicated personnel and equipment are seldom used (Aylen *et al*. 2007 [3+]).

7.39 Pineda & Rigo (2017 [2+]) note that in Catalonia, **Spain**, ignition control and extinction represents the most important wildfire management option and accordingly, a network of observers is deployed every summer to report any seat of fire. The campaign covers a four-month period from June to September, months that encompass 60% of forest fires and 95% of lightning-induced wildfires, though no evidence was provided on its effectiveness in preventing, or reducing the impact of, wildfires.

Evidence gaps and research recommendations on fire watching

7.40 Assessment of the available evidence summarised above suggests that the following areas would benefit from further research, monitoring or other investigation:

a. In reviewing factors associated with wildfire severity and impact, potential impact should also be considered. This includes inputs (e.g., guidance and effectiveness) to risk registers, and tools developed for wildfire management planning including risk assessment, scoring and mapping and fuel mapping.

b. Exploration of the use and effectiveness of fire watching and other (including automated) Early Warning Systems, and when they are best deployed.

8 Reducing the impact of wildfires

8.1 The full text of question 8 is:

What are the most effective measures for reducing the negative impacts of wildfire?

Introduction

8.2 Measures for reducing the impact of wildfires are here taken to comprise the ‘fire management’ activities in the Prestemon *et al*. (2013 [3+]) conceptual model (adapted in Figure 1): prescribed fires, fuel treatments and suppression/firefighting. There is some overlap with wildfire prevention (Section 7), and related questions, particularly in relation to firebreaks and fire watching.

8.3 A Forestry Commission Technical Note on *Forest and moorland fire suppression* evaluates and reviews firefighting techniques, methods and equipment, including the use of waterless, foam and water-based systems based on FC trials on *Calluna* and *Molinia*, fire breaks and helicopters, and makes recommendations on best practice (Murgatroyd 2002 [3+], see para. 8.14 below). Further FC guidance provides information to land owners on how they can use design planning to improve wildfire response and fire suppression (Forestry Commission 2014, para. 7.11).

Summary of evidence on reducing the impact of wildfires

Managing fuel load in the UK

8.4 Whilst monitoring and managing fuel load is often advocated in the UK, especially for upland heathland and peatland habitats (e.g. McMorrow & Lindley 2006 [2+], Albertson *et al*. 2010 [2+] and Marrs *et al.* 2018 [2+]), there appears to be limited evidence of its direct effect on wildfire ignition, behaviour, severity and extent, or in reducing wider negative impacts. Where carried out in the UK, managing fuel load is mostly done by managed burning (rather than by mechanical treatments, especially cutting/mowing though this is increasing on moorland, or grazing and herbicide use), principally for other objectives, particularly game (red grouse) and livestock management (e.g. Defra 2007; Douglas *et al*. 2015; also see para. 5.29), though fuel reduction may be a potential co-benefit.

8.5 The Forestry Commission’s guide on *Building resilience into forest management planning* provides guidance on managing vegetation and fuels for land managers in forestry and associated open habitats which includes vegetation management (i.e. forestry operations, mechanical cutting), grazing and burning using a matrix linked to Wildfire Management Zones to ensure a proportionate approach at both site and landscape scales (Forestry Commission 2014).

Managing fuel load outside the UK

8.6 Managing fuel load by mechanical treatments and/or prescribed (and sometimes ‘traditional’ managed) burning is widely practiced elsewhere in the world, particularly in shrub and forest habitats in southern **Europe**, **North America** and **Australia**, and there is strong, but in some cases contradictory (with regard to specific aspects), evidence particularly from modelling and theoretical investigations, and in some cases empirical studies, that this can be beneficial in reducing hazard and hence the incidence, intensity, severity and extent of wildfires, and in facilitating fire suppression efforts, (Hering *et al*. 2009 [2++], Marino *et al*. 2012, 2014 [both 2++], Stevens-Rumann *et al*. 2013. [2++], Brose & Wade 2002 [2+], Nunez-Regueira *et al*. 2002 [2+], Shang *et al*. 2004 [2+], King *et al*. 2006 [2+]), Cary *et al*. (2009 [2+]), Mitchell *et al*. 2009 [2+], Cassagne *et al*. 2011 [2+], Arkle *et al*. (2012 [2+]), Shive *et al*. 2013 [2+], Wu *et al*. 2013 [2+], Volkova *et al.* 2014 [2+], Waltz *et al*. (2014 [2+]), Penman *et al*. 2015 [2+], Oliveira *et al*. 2016 [2+], Fernandes & Botelho 2003 [3+] and McCarthy & Tolhurst (2001, 2004 [3-]). However, the magnitude and length of the effect, and the cost/benefit ratio, trade-offs and difficulty of implementation vary between sites, habitats, and wider landscapes including at the interface with habitation. In addition, operational, social, ecological and wider environmental issues and objectives may constrain fuel load management.

8.7 There is less extensive evidence on the effects of fuel management from empirical (rather than modelling and theoretical) studies, mostly from case studies and analysis of fire regimes in the presence of fuel management, especially of prescribed burning. More generally, there is moderate evidence that there remain considerable apparently unresolved questions over the effects of fuel load management, in particular in relation to the spatial arrangement, size, extent and type of fuel treatments, and severity of fire weather conditions (Keeley *et al*. 1999 [2+], Keeley & Fotheringham 2001 [2+], Cary *et al* 2009 [2+], Price 2012 [2+] and Fernandes & Botelho 2003 [3+]). As a result, Fernandes & Botelho (2003 [3+]) suggest that “the conclusions that can be drawn from these approaches are limited, highlighting the need for more, properly designed experiments addressing [the] question [of fuel treatment effects]”). This includes the following moderate evidence mostly in shrub and forest, and in some case grassland, habitats, especially from southern **Europe**, **North America** and **Australia**, that the effectiveness of fuel treatments, especially prescribed burning, in reducing the area affected by, and intensity and severity of, subsequent wildfires is influenced by a range of factors:

a. While prescribed burning can be effective at reducing fuel load (e.g. by about 50–60% in dense stands and 60–80% in more sparse in **French** Mediterranean habitats ranging from grassland, garrigue shrublands to forest and woodland, in the first year after treatment, Cassagne *et al*. 2011 [2+]), relatively rapid, though variable, fuel accumulation rates frequently limit effectiveness to a relatively short post-treatment period, often as short as a few years in more open habitats, though this varies by site and habitat type (Cassagne *et al*. 2011 [2+], Arkle *et al*. 2012 [2+]), Fernandes & Botelho 2003 [3+]). Nevertheless, fuel management may also provide assistance with access to allow fire suppression, though McCarthy & Tolhurst (2001, 2004 [3-]) considered an average burn frequency of 11 years in **Australia** was sufficient to allow fuel hazard to increase to levels of more than 'high’, after which 'very high' or 'extreme' fuel hazard levels are reached and the effect of previous fuel reduction burning on wildfire behaviour is minimal.

b. The spatial pattern, size, shape and continuity of prescribed burning influence its effectiveness in reducing the area affected by subsequent wildfires (Price *et al*. 2007 [1++], Arkle *et al*. (2012 [2+]) and Fernandes & Botelho (2003 [3+]), with simulations suggesting that long linear (gridded) barriers are more effective than patch barriers (Price 2012 [2+]), though gaps in firebreaks, other barriers or a grid lead to reductions in effectiveness (Price *et al*. 2007 [1++] and Price 2012 [2+]). However, a review by Fernandes & Botelho (2003 [3+]) suggested that “optimisation of the spatial pattern of fire application is critical but has been poorly addressed by research and practical management guidelines are lacking to initiate this.” Modelling by King *et al.* (2008 [2+]) suggested that treatment level (up to 50% area per annum) of **Australian** buttongrass moorland had the greatest influence in modifying fire effects, whereas treatment unit size had the least.

c. Similar to spatial arrangement (above), the overall extent and frequency (level) of prescribed burning influences effectiveness in reducing the area affected by wildfire (Bradstock *et al*. 1998b [2+], King *et al*. 2006, 2008 [both 2+] and Price 2012 [2+], Bradstock *et al* 1998a [2-]). Relatively high proportions of an area are likely to be required to be subject to prescribed burning annually (short rotation length) to have an effect on the area affected by subsequent wildfire, though this can result in as much or more being subject to burning (prescribed and wildfire) in total and/or the treated area exceeding the reduction in area of wildfire (Price & Bradstock 2011 [2++]), Bradstock *et al*. 1998b [2+], Piñol *et al.* 2005 [2+], King *et al.* (2008 [2+]), Bradstock *et al* 1998a [2-] and McCarthy & Tolhurst (2004 [3-]), though the area burnt is not the only important factor and there may be trade-offs regarding severity and impact of burning and wildfires, e.g., see para. 8.8a below and Summary para. 9.68).

d. Other factors, in particular variation in weather, and success of ‘ignition management’ (prevention), may also be important, or more important, in explaining variation in area burned by wildfire than fuel management approach and effort (Keeley *et al*. 1999 [2+], Keeley & Fotheringham 2001 [2+] and Cary *et al*. 2009 [2+]). Piñol *et al*. (2005 [2+]) addressed these competing ‘meteorological’ and ‘fuel’ hypotheses, using modelling of the relationship between fuel accumulation, weather and prescribed burning in Mediterranean regions of **Spain** and **Portugal** which showed that the total area burnt (by prescribed burns and wildfires) was similar despite any effort to reduce it by extinguishing fires or by using prescribed burning. Nevertheless, no burning (fire exclusion) slightly enhanced the dominance of large wildfires compared to using prescribed burning. The relative importance of weather is likely to vary between meteorological regions and particularly meteorological variability, probably becoming more dominant with greater variability (Piñol *et al*. 2005 [2+]).

e. The best results of prescribed fire application are likely to be attained in heterogeneous landscapes and in climates where the likelihood of extreme weather conditions is low (Fernandes & Botelho 2003 [3+]).

f. Modelling of sagebrush habitats in Wyoming, **USA**, showed that, whilst fuel treatments were economically efficient in relation to wildfire suppression when the ecosystems are in their healthiest ecological states, treatment is not efficient in degraded ecological states dominated by invasive plants (Taylor *et al*. 2013 [4+]).

Natural fire regimes

8.8 There is moderate evidence internationally that ‘natural’ fire regimes, without complete fire suppression, can result in landscapes that are more self-regulating and resilient to wildfire (Ramos-Neto & Pivello 2000 [2+], Keeley & Fotheringham 2001 [2+]), Parks *et al*. 2014, 2015, 2016 [all 2+] and Thompson *et al*. 2016 [2+]). This includes the following moderate evidence:

a. Parks *et al*. (2014, 2015, 2016 [all 2+]) explored various aspects of whether natural wildland fire regimes can result in landscapes that are both self-regulating and resilient to fire. Parks *et al*. (2014 [2+]) investigated whether a previous wildland burn on an area moderated the severity of a subsequent wildland fire in two **US** wilderness areas in New Mexico and Idaho. Burn severity was significantly lower in areas that had recently been burned through wildland fire. As the time interval between fires increased, the severity of the subsequent fire increased, with the moderating effect of a previous fire lasting at least 22 years. As a result, fires can and do self-regulate from a burn severity perspective. They suggested that, together with other research, this provides a rationale for using wildfire as an effective "fuel treatment". Parks *et al*. (2015 [2+]) evaluated the ability of wildland fire to create barriers that limit the spread of subsequent fire in four large wilderness and national park areas in the western USA. They found that wildland fire limits subsequent fire spread but that this effect decays over time, ranging from 6–18 years depending on the study site. The effect was substantially reduced under extreme, compared to moderate, conditions in all four study areas. Parks *et al*. (2016 [2+]) further investigated whether wildland fire regulated the ignition and spread (occurrence) of subsequent fire in the same four wilderness areas. The results showed that wildland fires did regulate subsequent fire occurrence with the longevity of the effect varying by study area ranging from nine to over 20 years. They noted that multiple lines of evidence indicate that feedbacks associated with wildland fire regulate several aspects of subsequent fires: the severity, size and occurrence. When these feedback effect mechanisms are interrupted by human activities such as fire suppression, the result is larger and more severe fire in future years.

b. Thompson *et al*. (2016 [2+]) present a case study of a wildfire across a mixed, mostly forested area in New Mexico, **USA**, to explore the role of previously burned areas (wildfires and prescribed fires) on suppression effectiveness and avoided exposure. The fire exhibited rapid growth under extreme weather conditions that meant that there were limited opportunities to bring the fire under control. Previous large fires exhibited significant but variable impacts of suppression effectiveness and fire spread potential, but in aggregate likely helped avoid greater loss especially in the case of a very large previous wildfire. It was suggested that human decision-making influences the location and effectiveness of the line chosen to attempt to burnout vegetation in the path of a fire. Recognising the presence of previously burned areas could lead to more and better opportunities for controlling fires.

c. Keeley & Fotheringham (2001 [2+]) investigated natural historic fire regimes in Californian shrublands, **USA**, to answer the question of whether they had altered the landscape to one that prevented large wildfires. There was no evidence that current fire management policies had created the contemporary fire regime dominated by massive Santa Ana wind-driven fires. Santa Ana-driven fires are not dependent on an unnatural accumulation of fuel, but appear to be a natural feature of this landscape. The determining factor in whether a fire becomes large was the coincidence of an ignition with severe fire weather. Fires ignited under severe weather conditions defy suppression, thus fire managers have made limited progress in reducing the number of catastrophic fires. Increased expenditure on fire suppression and increased loss of property and lives are the result of human demographic patterns that place increasing demands on fire-suppression forces.

d. Ramos-Neto & Pivello (2000 [2+]) monitored lightning fires in a **Brazilian** savanna National Park between 1995 and 1999. Though previously considered rare, lightening fires were frequent in the wet season and were considered likely to represent the natural fire pattern. They tended to be patchy and be extinguished primarily by rain, and created natural barriers to the spread of human-induced winter dry season fires.

Fire suppression/firefighting

8.9 Limited published evidence was identified on the effectiveness of wildfire suppression/ firefighting in the UK, though Forestry Commission guidance provides information to land owners on how forest design planning to improve response and fire suppression (Forestry Commission 2014, para. 7.11). This highlights forestry management techniques that are also applicable to open habitat management for planning for an incident response, which includes several components. Firstly, improving access to water (lakes, rivers, streams, fire ponds and dams, fire hydrants and high-volume pumping units), access considerations (reducing obstacles for fire appliances, providing space and hardstanding for temporary fire water dams, improving helicopter suppression and landing zones, use of 'one way' systems, and entry and exit points to sites) and protecting the environment (pollution from water runoff from either firefighting operations, use of interceptors, reducing impact to aquatic habitat and use of foam and other chemicals). Secondly, improving response to wildfire incidents, including planning for access by Fire and Rescue Services and planning out of 'control lines' (such as fire and fuel breaks and use of natural features) to improve fire suppression activities as defined in a Wildfire Response Plan.

8.10 There is moderate evidence from the Peak District, UK, that resources and interventions that support a rapid, reliable and effective response to a wildfire such as fire watching (also see Section 10), improved vehicle access and provision of emergency ponds may show a high return on investment in terms of fire rescue resources saved, even if dedicated personnel and equipment are seldom used (Aylen *et al*. 2007 [3+]).

8.11 In Forestry Commission trials on the use of waterless, foam and water-based control systems, there is strong evidence that the back fire, flanks and fire head (see Appendix 10) were effectively suppressed in *Calluna* stands, though in *Molinia* test fires only the back fire and flanks were suppressed because the head fires moved very quickly and were confined by fire breaks (Murgatroyd 2002 [3+]). In some test conditions, greater fire intensities were experienced with small fuel loads with a fast rate of spread (ROS), compared to fires with large fuel loads with a slow ROS. With waterless suppression using belt and wire-mesh beaters, a conveyor belt head was best in *Molinia* fires (with mesh heads unsuitable as flaming grass could become entangled in the mesh and help spread the fire), whereas in *Calluna* fires long-handled wire mesh beaters were most effective. Water suppression was tested using high-pressure portable pumps and very high pressure (low volume) pumps each using jet stream, spray and fog patterns. The combined use of a fogging system and a team of beater operators was found to be the most efficient fire suppression method in both *Molinia* and *Calluna* fires (the fogging system was used to knock down and extinguish most of the fire front with beater support 5 m to 10 m apart to extinguish any remaining fire and subsequent flare ups).

Evidence gaps and research recommendations on reducing the impact of wildfires

8.12 Assessment of the available evidence summarised above suggests that the following areas would benefit from further research, monitoring or other investigation:

a. Incorporation of socio-economic aspects of wildfires in consideration of monitoring and research on their occurrence, severity, extent and impact, and in wildfire prevention and management/control (reducing impact). This could be done separately or ideally be integrated with biophysical research, but in either case, the findings ought to be interpreted holistically. It should involve engagement with the wildfire community, other stakeholders, land managers and the public.

b. Investigation of the relationship between routine managed burning and prescribed burning (and cutting/mowing and other management with a fuel management objective), and wildfire occurrence, extent, and ideally severity and impact. This should consider the potentially beneficial effect of fuel management and how factors such as the scale, pattern frequency and targeting (in relation to risk factors) affect this, and the effect of burns escaping control resulting in wildfires and the factors that contribute to and cause loss of control. The latter could include consideration of indirect effects such as effects of managed/prescribed burns on vegetation composition (e.g., dominance of potentially flammable vegetation types) and water table (lowering).

c. Linked to (b) above, investigation, potentially involving modelling, of the most effective burn configuration (patch size, shape, pattern, scale, frequency) and targeting of managed/prescribed burning to manage fuel load to reduce wildfire occurrence, severity, extent and impact. This would need to consider habitat/vegetation type and composition, including types other than just *Calluna*-dominated vegetation.

d. Extension of recording/mapping of managed/prescribed burning in England potentially using Earth Observation, particularly in the uplands, in part to contribute towards investigation of the relationship with wildfire occurrence.

e. Similar to (b) above and potentially linked to restoration, a broader investigation of the effects of wider management interventions, e.g., grazing, scrub and bracken management, and drainage, on wildfire occurrence, severity, extent and impact.

f. In reviewing factors associated with wildfire severity and impact, potential impact should also be considered. This includes inputs (e.g., guidance and effectiveness) to risk registers, and tools developed for wildfire management planning including risk assessment, scoring and mapping and fuel mapping.

g. Further research on the design and effectiveness of fire and fuel breaks, and fire suppression in open habitats (and forestry).

h. Exploration the effectiveness of Wildfire Risk and Fuel Maps and associated guidance, and the role they may have in wildfire prevention and control/management.

i. Investigation of the natural (and historic) fire regime in the UK (probably involving paleoecological, and perhaps restoration/reconstruction ecology, review including contemporary studies), its impact upon vegetation communities, including an assessment of the extent to which they are fire-adapted, and hence the implications for the use of fire in managing UK vegetation.

9 Summary, interpretation and conclusions

9.1 In this review, evidence was identified in relation to the overarching topic of the causes, prevention and management of wildfire on heathlands, peatlands and other open, semi-natural habitats in England, which was broken down into eight specific questions (Sections 4–8). This section summarises the evidence statements developed for each question and presents overall conclusions and research recommendations.

9.2 The evidence statements have been summarised and simplified including removing study references and descriptions (though links are given to the corresponding paragraphs in the main text from the evidence sections), and further synthesis within groups of related statements, especially where a series of statements support a higher level, broader statement (para. 3.5), and within questions and headings/themes and to a limited extent across them. Some further explanation and interpretation including of the wider context has been included within and across questions, where appropriate supported by evaluated and non-evaluated references.

9.3 A total of 137 evidence statements were developed (Sections 4–8) from the evidence derived from 174 evaluated references (paras. 2.14–2.18 and Tables 1–4). All of the statements were classed as either strong (42%) or moderate (58%), with none weak or inconsistent (Table 6). There were differences in the quantity and quality of evidence, and hence strength of evidence statements in relation to the eight questions. There was a considerable volume of mostly strong and moderate evidence statements on wildfire risk and occurrence (51 evidence statements), and ignition sources (42), but much more limited, mostly moderate evidence statements on fire behaviour and severity, prevention and reducing impact (Table 6).

Table 6. The number and strength of evidence statements by review question.

Question	Strong	Moderate	Weak	Inconsistent	Total
Risk and occurrence	31	20	0	0	51
Ignition sources	21	21	0	0	42
Behaviour and severity	0	7	0	0	7
Prevention (general)	1	6	0	0	7
Firebreaks	0	4	0	0	4
MOFSI	2	8	0	0	10
Fire watching	0	1	0	0	1
Reducing impacts	2	13	0	0	15
Total	**57**	**80**	**0**	**0**	**137**

Wildfire risk and occurrence

General wildfire occurrence in the UK

9.4 There is strong evidence that risk and occurrence of wildfire in the UK is associated with particular weather conditions (typically dry, warm conditions, especially severe and/or prolonged drought, or, particularly in spring, low temperatures and frozen conditions);

vegetation characteristics, especially of the dominant plant species, particularly *Calluna* and *Molinia* (including plant functional type, autecology, phenology, age/growth stage and height/structure, (high) fuel load and fuel structure, and (low) moisture content); and human-related factors (accidental ignition associated with public access, recent or current wildfire and managed burning activity, and arson) (para. 4.11). There is also moderate evidence that physical environment characteristics, for example, geographic location, altitude, topography including slope, aspect and soil type, and remoteness, may contribute to risk or may be linked to some of the other main risk factors listed above (para. 4.12).

Geographic distribution in the UK

9.5 Strong evidence indicates that wildfires occur widely in GB, including in all English regions, but more frequently in some, though the regional pattern varies between frequency of incidents, area burned, and wildfire cause/type reported (para. 4.14). This is supported by strong evidence from seven evidence statements from four national and two regional/local data sets and studies (para. 4.14a-h). This includes a GB analysis (of 'NOGP-type' wildfires from IRS data over three years to 2012, para. 4.7a and 4.14a) showing that wildfires occur in all regions with high concentrations identified in south Wales (supported by a regional study, para. 4.14h, south-east England and the southern Pennines, while two Scotland-wide analyses (para. 4.14g) show a high frequency in Highland region which may at least in part reflect its large size.

9.6 The key Forestry Commission analysis of English IRS data (over eight years to 2016/17, para 4.3) shows that 'all wildfires' occur across all English regions with frequency highest in the North West (40,114 incidents, 16%), followed by Yorkshire and the Humber, West Midlands and South East all with over 30,000 incidents (13–14%), and least in the South West (7%) (para. 4.14b). This probably reflects the very high incidence of small fires (para. 4.26), particularly in urban and urban-fringe areas (para. 4.22b), in regions with large urban conurbations. The region with the greatest number of wildfire incidents per km^2 of land area is the most urbanised, namely London (with 16 wildfire incidents per km^2 over the eight-year period), while the region with the least is one of the least urbanised, the South West (with 0.7 wildfire incidents per km^2 over the same period) (para. 4.14c).

9.7 The pattern differs for area burned (para. 4.14c) with the largest area still in the North West with 50% of the total area (18,879 ha, also equating to the highest area per km^2, an average of 1.3 ha/km^2 over four times the average for England as a whole, para. 4.14e), perhaps reflecting some large fires over the period, but is then followed by the rural South West (19%), which in contrast had the lowest frequency of wildfires, probably reflecting spring heath and grass-moor fires on the SW Moors, followed by Yorkshire and the Humber (15%), with no other region with more than 7%.The pattern by area broadly reflects the distribution and extent of heathland and 'wetland' (mostly blanket bog), with the largest areas in Yorkshire and the Humber and large areas in the NW, NE and SW (Natural England 2008), though this relationship would benefit from further analysis including using narrower habitat types, e.g. by BAP Priority Habitats. The region with the second greatest area burnt per km^2 is Yorkshire and the Humber (0.4 ha/km^2), followed by the South West (0.3 ha/km^2), then in descending order by London, the South East, Eastern, East Midlands, West Midlands and North East (para. 4.14e).

9.8 Data collated by Natural England on 127 wildfires on open, semi-natural habitats (over seven years to 2018, para. 4.6) show that more occur in the lowlands (56%) than uplands (44%), and that they occur in all regions (apart in this data set from London), with a slightly different pattern to the IRS data with most in Yorkshire and the Humber and South East (both 25%), followed by South West (21%), North West (13%), North East (7%), West Midlands (4%), East Midlands (4%) and Eastern (2%) regions (para. 4.14f), though this may differ by area (which was not included in the analysis of this data set).

9.9 On a smaller sub-regional scale, data recorded by National Park rangers from over 400 fires over a 33-year period (up to 2008, para. 4.7d and 4.14i) show that wildfires are frequent in the Peak District, it was suggested "… reflecting the high visitor numbers and density of potential access-related ignition sources combined with what were considered to be vulnerable moorland habitats", though this high incidence is not reflected in the data for the wider East Midlands region (para. 4.14b,d,f), perhaps reflecting the smaller area of heathland and blanket bog in the region compared to some other, especially northern, regions, most notably Yorkshire and the Humber (Natural England 2008).

Seasonal and other timing in the UK

9.10 Strong evidence indicates that peaks in, and coincidence of, at least some risk factors (para. 4.11) are associated with increased wildfire incidence in the UK in summer and especially spring (para. 4.15). This includes evidence from seven supporting evidence statements (six strong and one moderate) from five national and two regional/local data sets and studies (para. 4.15a-g) of a strong seasonal pattern, with a marked spring peak, especially in April and in the uplands, which extends generally at a lower level (but with occasional peaks related to fire weather which may involve large fires) through summer, with much lower frequency in autumn and winter. For example, 59% of events and 95% of the burned area occurred in spring in a GB-wide analysis of IRS data (para. 4.15a) and 48% of events occurred in spring in English wildfire data held by and submitted to Natural England, with 34% in summer (para. 4.15b). The Natural England data set also shows a greater proportion of wildfires in the uplands in spring (67%) than in the lowlands (44%) where there was a more even spread across spring and summer (para. 4.15c). The spring peak probably results from a number of factors, including physiological drought of *Calluna* during cold, clear and frozen conditions (para. 4.20) and/or improving warm, dry weather and easterly winds (para. 4.18e,f), creating suitable conditions for ignition from accidental sources, including from increasing numbers of visitors to the countryside (Herbert *et al*. 2015) and escaped managed burns (up to the end of the burning season which extends to 31 March in the lowlands and 15 April in the uplands, Defra 2007), and arson. However, visitor numbers, for example, to upland National Parks, peak in summer (Appendix 3, Table A3.1) when wildfire frequency and extent is normally lower than in spring, particularly in the uplands (para. 4.15).

9.11 There is moderate evidence of slightly increased wildfire incidence at weekends and during school and bank holidays, probably associated with increased levels of public access and both accidental fires and arson (para. 4.16). This includes moderate evidence from two supporting evidence statements, one a national data set and the other a regional study (para. 4.16a,b). There is also moderate evidence from south Wales that incidence of fires builds steadily through the day peaking in the late-afternoon/early-evening, later on weekdays than at weekends (para 4.17). Throughout the mid-spring/summer months (April to August) the percentage of fires later in the evening increases, suggesting "… that fires start outside work and school hours [and] … a link between the timing of fires and the daily routines of firesetters" in a deprived area where most fires were attributed to arson, para 5.35 close to access points (para. 5.9).

Weather and trends in wildfire occurrence the UK

9.12 The UK has a relatively uniform annual rainfall pattern with no regular dry season, "… though short droughts of [a month or more] often occur that can lead to catastrophic wildfires". Strong evidence indicates that the incidence of wildfire, especially large wildfires, in GB is episodic, coinciding with dry-spells and hot periods, with much variation between years which makes determination of temporal trends difficult (para. 4.18), especially as collation of data nationally is relatively recent (para. 4.3). However, frequency is predicted to increase in response to climate change (Albertson *et al.* 2010 [2+], Wentworth & Shotter 2019 [3+] and Cavan *et al.* 2006 [3+]) and perhaps other factors, and there is evidence from elsewhere in the **world** that this is occurring (Woolford 2014 [2++] and Wentworth & Shotter 2019 [3+]), though declines in area burned have also been reported (para. 1.7).

9.13 This includes evidence from seven supporting evidence statements (three strong and four moderate) based on four national and three regional/local data sets and studies (para. 4.18a-g) which overall show relatively wide annual fluctuations, with occasional peaks related to fire weather, sometimes over several years, but no clear temporal trend in the annual frequency of wildfires, albeit that to date most data sets are relatively short. For example, the FC analysis of English IRS data (over eight years) shows relatively wide fluctuations, but no clear trend, in the annual frequency of 'all wildfires', with peaks in the first three years linked to periods of dry, warm conditions between 2010 to 2012, and lower frequency in other years (para. 4.18a). A similar pattern is evident for the area burned per year, with peaks in the first three years and less variation in all other years, and in frequency and area for the far fewer NOGP fires (para. 4.18b).

9.14 An analysis of operational Met Office Fire Severity Index (MOFSI) outputs for England and Wales indicates that the summer of 2018 (not included in the FC analysis above) saw "… more extensive, long-lasting and more severe fire weather conditions [than in] the previous four years" for which records were available and (from satellite-derived burn area data over a longer, 15-year period back to 2003) the greatest area burnt, and hence it was an "unusually extreme but not unprecedented year for wildfires, with the burnt area being slightly greater than, but comparable to, previous severe fire years such as in 2003 and 2006" (para. 4.18c).

9.15 There is moderate evidence from the West Pennines and Peak District that wildfires are associated with easterly winds and, from south Wales and the Peak District, with rising daily temperature, and that incidence reduces during periods of rainfall though it can increase soon after this ceases (para. 4.18e-g).

Moisture content of vegetation in the UK

9.16 Related in part to weather (and also to season, habitat, plant and fuel type, and phenology), there is strong evidence from the UK that risk of ignition and spread is heightened when vegetation fuel moisture content in the typically *Calluna*-dominated canopy and/or bryophyte/litter layer is relatively low or reduced in response to cold weather, for example, when moisture content of *Calluna* is around 60% or lower and 140% or lower for the bryophyte layer (para.4.20). This is supported by moderate evidence that physiological drought may be caused by cold, clear weather and frozen ground, and winter cuticle damage, which can reduce the fuel moisture content of live biomass and create the potential for ignition and extreme fire behaviour, particularly in spring (para. 4.20a). In addition, that reduced fuel moisture content of moss/litter and soil in a UK heath led to increased fire-induced consumption of the moss/litter layer and increased soil heating compared to a raised bog site, leading to increased fire severity (para. 4.20b). Little evidence was identified on temporal trends (other than a link to weather) or spatial trends in fuel moisture content or for vegetation types dominated by species other than *Calluna*.

Habitat and vegetation types

9.17 There is strong evidence that wildfires in GB occur relatively widely and cover the greatest area on open, semi-natural habitats, especially moorland habitats (particularly upland heathland and peatland) and lowland heathland, and to a lesser extent on semi-natural grasslands, though the frequency of incidents (but not area) is greater on woodland, agricultural ('improved' grassland and arable) land, and especially in urban areas (para. 4.22).

9.18 This includes evidence from five supporting evidence statements (three strong and two moderate) based on two national data sets and two regional/local data sets and studies (para. 4.22a-e). For example, in a GB-wide analysis by far the largest area (50% from just 11% of incidents) occurred on 'heath/bog/marsh', with the next largest area on grassland (24%), broad Land Cover Map (LCM) categories (para. 4.22a). Similarly, the FC analysis of IRS data shows that though only 5% of incidents occurred on open, semi-natural habitats, they covered the majority by area (total area 36,925 ha, 59%), comprising 'mountain, heath and bog' (48%, very similar to the GB data above), semi-natural grassland (11%) and coastal, freshwater and saltwater combined (0.3%), with the remainder on improved grassland (18%), arable (11%), woodland (9%) and built-up areas and gardens (4%) (para. 4.22b). As might be expected, designated sites are significantly affected with a total of 7,042 incidents covering 10,320 ha (mean 1,290 ha/year) in SSSIs and smaller numbers and areas in SACs (2,677, 8,386 ha), SPAs (2,874, 5,496 ha) and Ramsar Sites (1,203, 225 ha) (para. 4.22c).

9.19 Moderate evidence indicates that the flammability of peat/litter fuel-beds on UK heathland/moorland differs depending on the intrinsic characteristics of the species making up the fuel layer (para. 4.23). In the upper canopy layer, often composed mainly or solely of *Calluna*, the probability of ignition is influenced by the proportion of dead fuel accumulated within the vegetation and the moisture content. Older *Calluna* stands "have a high biomass of woody matter and hence represent a wildfire hazard due to their high fuel load" (but see para. 9.63). However, there is limited evidence on flammability of other UK species/vegetation types.

9.20 There is moderate evidence from continental **Europe** and **North America** that 'pristine' and 'less-modified' peatlands, especially where the water table is high, are less vulnerable to severe, smouldering fires (para. 4.24).

Extent and size of wildfires in the UK

9.21 There is strong evidence that NOGP/NOGP-type wildfires in GB are widespread and relatively extensive, covering, for example, 17,203 ha/year in GB over a three-year period (2010–12) and 4,434 ha/year in England over eight years (2009/10–2016/17), with the vast majority small in size, for example, 99% less than 1 ha in England (para. 4.26). Large, very large and landscape scale fires, and fires on semi-natural habitats (para. 4.22), account for a disproportionately high proportion of the total area burnt, though data on the total area burnt by size class was only available for an upland sub-sample of the FC IRS data. Nevertheless, there is considerable annual variation in the area burnt (para. 4.18) reflecting episodic severe fire weather, with data required over a longer period to better assess the area subject to wildfire in England and the UK.

9.22 This is supported by four other evidence statements (three strong and one moderate) from three national data sets and one local case study (para. 4.26a-d) which show a preponderance of smaller fires. For example, the FC analysis of IRS English data shows that the vast majority of incidents are 'small' (<1 ha, 155,957 incidents, 99% of incidents), with few 'medium' (1–49 ha, 0.6%) and very few larger: 'large' (50–99 ha, 0.02%), 'very large' (100–999 ha, 0.03%) and 'landscape scale' (>1,000 ha, 0.003%) UKVFS fire size categories (para. 4.26b). Data compiled by Natural England for open, semi-natural habitats show that such wildfires tend to be larger with most falling into 'medium' (59% of fires) or 'small' (28%) UKVFS fire size categories, but, as with the IRS data set, far fewer 'large' (3%), 'very large' (8%) or 'landscape-scale' (2%) incidents (para. 4.26c).

9.23 Larger fires tend to be episodic (para. 4.18). Although 'very large' and 'landscape-scale' fires occurred in four of the seven years included in the Natural England data set, there was more than one in only two years (para. 4.26c). However, small fires may be severe and have impacts, for example, on buildings and other infrastructure, especially at the rural-urban interface (RUI), and on particularly sensitive habitats and other features. Conversely, large fires are not always more severe and impactful (e.g., in the case of the Rum fire, Sargent *et al*. 2019, also see para. 1.9), though they lead to a periodic impact on a relatively large area of heathland and peatland and other open, semi-natural habitats (mean 4,615 ha/year and a total of 36,916 over the eight years of the IRS data set in the FCE analysis (para. 4.18a), with 48% of this corresponding to heathland and peatland and 59% to open, semi-natural habitats in total, para. 4.22b), albeit this is a relatively small proportion of the total heathland and peatland area of around 560,000 ha and the over a million hectares of open, semi-natural habitats in total (para. 1.18–1.20).

Wildfire ignition sources

General ignition sources

9.24 There is strong evidence that when conditions lead to risk of a wildfire event, most ignitions in the UK are anthropogenic in origin, either accidental, associated with concentration of public access, recent/current wildfire or managed burning activity, or deliberate (arson), with very few documented instances of 'natural' wildfires due to lightning strikes (para. 5.13). This includes strong evidence from two supporting evidence statements based on a national Natural England data set and data submitted to this review (para. 5.6a,b). Where a broad cause of fire was assigned (2,726 fires), the majority (77%) were classed as deliberate (arson) and the minority (23%) accidental, with a higher proportion deliberate in the lowlands (80%) than the uplands (55%), though the majority of fires were in the lowlands (88%), where they tended to be smaller in area (para. 4.26c). In a minority of cases where a more specific cause was assigned (382, only 12% of all fires), the main specific causes were 'camp fires' (49%), land manager burns (15%), barbeques (10%), and 'reignited' fires and military training (both 5%) with no other individual causes greater than 3% of incidents.

9.25 In the above data sets, there is strong evidence of differences between the lowlands, where the pattern was more similar to that overall (reflecting the fact that the majority of fires with a specific cause assigned were in the lowlands) with most due to camp fires (56%), barbeques (11%), 'reignited' fires (8%) and land management burns (8%), whereas in the uplands the majority were assigned to land manager burns (68%), followed by camp fires (9%) and barbeques (8%) (para. 5.6b). Care is needed in interpreting these findings given the small proportion of overall fires where a more specific cause was assigned and potential subjectivity and bias in the assessment of cause, and the relatively small number in the uplands (62, 10% of all upland fires) which emphasises the need for better recording of information, including cause, on wildfire incidents. These data relate to incidence of wildfire and little information was identified on the relationship between ignition cause and area burned, though in one local upland study the area burned was greater as a result of escaped managed burns than other causes (para. 5.32c).

9.26 **Away from the UK**, there is similar strong evidence that most wildfires are anthropogenic in origin, with some specific accidental causes such as power lines and machinery more common, and lightning a more frequent natural cause in some regions (para. 5.7). In addition to lightning, natural ignitions can also potentially result from volcanic activity and geological friction.

Association with access and proximity to habitation and development

9.27 Strong evidence from the FC analysis of English IRS data over eight years indicates that between 21% and 28% of 'primary fires' per year occurred in built-up areas and gardens (para. 5.9). There is also strong evidence from south Wales (2000–08, para. 4.7b) that wildfires are associated with public access, especially on or near the rural-urban interface, with over 90% of 'grassfires' recorded within 100 m of a road or public right of way (PROW) and 99% within 500 m of a road or PROW (para. 5.9, also see para. 5.35 under Arson, regarding a similar link with deprivation). Similar moderate evidence from the English Peak District indicates that fires are more frequent near to access routes such as roads and footpaths, and on certain days of the week, especially at weekends, and school and bank holidays, associated with increased levels of public access (para. 5.10, also see para. 4.16a,b regarding increased wildfires at weekends and weekday evenings in south Wales and the Natural England national data set).

Lightning

9.28 As noted earlier, there is strong evidence that 'natural' wildfires in the UK due to lightning strikes are rare with very few documented instances and none included in recent (2002–18) English wildfire data held by and submitted to Natural England under this review (para. 5.13). **Away from the UK**, strong evidence indicates that lightning-induced fires, particularly from 'dry' lightning with no or little precipitation (which is less common in the UK where most is associated with precipitation, para. 5.12), are more frequent in some regions and countries, particularly in the Tropics, but also in southern Europe and North America (para. 5.14).

Hot metal particles and embers

9.29 Fuel beds can be ignited by hot metal particles (which can be generated by powerline interactions, friction of metal components, grinding, welding, overheated brakes, vehicle exhausts, and other sources of incandescent particles) and lofted flaming or glowing embers or 'firebrands' (from burning vegetation, wooden structures or material and interactions between powerlines and trees) (para. 5.15). There is strong evidence that hot metal particles and embers or firebrands can be carried relatively large distances by wind and are considered a frequent cause of fires in the **USA**, and have been reported from elsewhere, including **New Zealand**, **Australia** and **southern Europe** (para. 5.19).

9.30 Moderate evidence from recent wildfire data held by Natural England and submitted to this review indicates that ignition from hot metal particles or embers is uncommon in England, though a small number of incidences were recorded due to steam trains (4 cases), agricultural machinery (2), motor-cross bikes (1) and pyrotechnic devices (1) (all ≤1% of the 382 cases where a specific cause was given, para. **Error! Reference source not found.**).

Cigarettes

9.31 Cigarettes are often suggested as a source of ignition in accidental fires though there appears to be little published evidence on their importance and frequency in the UK. Nevertheless, moderate evidence from recent wildfire data held by Natural England and submitted to this review indicates that ignitions caused by cigarettes are uncommon in England with only six cases identified (1.6% of cases where a specific cause was given) and one due to a cigarette lighter (para. 5.22).

9.32 Strong evidence indicates a large reduction of the frequency of 'smoking-caused' wildfires across national forests and grasslands in the **USA** between 1980 and 2011 (to 10% of the 1980 level in 2011) reflecting a reduction in smoking rates (resulting in a 9% reduction in 'smoking-caused' wildfires), a reduction in incidents in states with regulations introduced requiring self-extinguishing 'less fire-prone' (LFP) cigarettes (estimated 23% reduction compared to states without regulations) and through improvements in wildfire cause reporting (48% reduction suggesting that a proportion of past fires were incorrectly classified as caused by smoking) (para. 5.23). The reduction due to regulations requiring LFP or 'reduced ignition power or propensity' (RIP) cigarettes which self-extinguish when left unattended is supported by strong evidence from ignition tests on household furniture in the UK and ignition strength tests in the **USA** which showed fewer furniture ignitions with RIP cigarettes (than filter-tipped cigarettes most popular at the time of the study which in turn showed fewer than untipped cigarettes) in the **UK** (Paul 2000 [2++]) and significantly reduced ignition propensity with RIP cigarettes (≤10% of 'full length burn' (FLB) compared with >75% FLB for non-RIP cigarettes) in the **USA** (para. 5.24). As a result of legislation introduced in 2011, all cigarettes sold in the EU must be of a reduced ignition construction (European Commission 2011).

Discarded glass

9.33 Moderate evidence indicates that radiant heating via the 'burning-glass effect' is unlikely to be a cause of ignition of northern forest fires in the semi-humid climate of **Germany** and no cases were identified from recent **English** wildfire data held by Natural England and submitted to this review (where a specific cause was given, para. 5.25). Schauble (2009 [4-]) used children's literature in **Canada** as an example of perpetuation of the notion that discarded bottles and broken glass are common causes of bushfire ignitions to demonstrate that cultural beliefs can lead to the ignoring of scientific evidence.

Ammunition and military training

9.34 Moderate evidence from recent wildfire data held by Natural England and submitted to this review indicates that ignitions associated with military training are relatively uncommon and, as would be expected, localised in England, with 21 cases identified (6% of the 382 cases where a specific cause was given, para. 5.26), though moderate evidence from recent MOD data identified 20 relatively small (≤5 ha) fires caused by military training over seven months in 2019 (para. 5.27). Moderate evidence from a study in the **USA** indicates that bullets can cause ignition of organic matter after impacting a hard surface, particularly those containing steel components or made of solid copper (para. 5.28). Fragments cool rapidly but can ignite organic matter, particularly fine material, if very dry and close to the impact site.

Managed burning in the UK

9.35 It has been suggested that there is limited information on the frequency of managed burns becoming out of control wildfires in the UK, though more is becoming available. This includes statistics on wildfire occurrence compiled nationally and locally, particularly by FRS (compiled nationally in the IRS since 2009, para 4.3) and for some National Parks and AONBs, though the cause of the fire is not always specifically determined or recorded. Together this provides strong evidence that managed fires escaping control cause a proportion of wildfires, particularly in the uplands (para.5.32).

9.36 This is supported by evidence from six strong or moderate (three each) evidence statements from four national and two regional/local data sets and across a range of study types (para. 5.32a-f). The proportion of incidents (with cause identified) caused by managed burns escaping control in two national data sets was 15% (57 cases) in recent (2002–18) English wildfire data collated by and submitted to Natural England and 60% (140 cases) “potentially caused by muirburn” in Scotland (IRS ‘primary’ wildfires, 2009/10–2014/15) (para. 5.32a,b). However, the percentage was much higher in in the uplands (68% c.f. 5% in the lowlands) in the English data set, probably at least in part reflecting the generally much wider use of managed burning in the uplands particularly in spring (para. 5.29) and lower incidence of deliberate and accidental fire setting, perhaps especially on more remote and extensive moorlands with lower levels of public access, compared to lowland heathlands where other accidental causes and arson are more frequent (paras. 4.14f and 5.6a,b). Three other smaller sample/regional/local data sets give percentage figures resulting from managed burns of 65% (11 cases) from a questionnaire survey of 41 Scottish estates, 36% from a local case study in the West Pennines (1995–2017) and 24% (10 cases) from Peak District National Park ranger reports (1976–2004), though in the last they tended to be much larger, causing 51% of the total area affected by wildfire (para. 5.32c-e).

9.37 Thus, these five studies give a range for the proportion of wildfires resulting from escaped managed burns of between 15% and 60%; 24–65% if data from the lowlands (where managed burning is much less common) in the English data set are excluded, though the studies cover different UK geographical areas and periods. There is a need for more complete data on escaped management burns and other causes of wildfires, and the area they affect. This could be achieved at least in part through more systematic recording of the cause of wildfires attended by the FRS through the IRS database and by other means, for example, potentially expansion of Natural England’s collation of records, especially for those not attended by the FRS.

9.38 In the questionnaire study of Scottish estates it was estimated that each of the 20 estates that conducted muirburn set an average of 215 fires a year, with one estate setting 900–1,000 (para. 5.32d). Thus, it was suggested that most of the fires set for management purposes are closely controlled and that very few escape, though Luxmoore (2018 [2+]) points out that this demonstrates the large scale of muirburn from which just a few escapes may potentially result in wildfires.

9.39 Data on wildfire occurrence over 18 years (to 2015) on Scottish National Trust properties covering an upland area of 63,316 ha where no managed burning takes place indicate there were 12 “large” wildfires covering a total of 1,463 ha or 2% of the upland area (equivalent to 0.1% of the area per year, para. 5.32f). The highest proportions burnt per individual estate were 19% and 17% at two (equivalent to 1% per year in both cases). It was noted that had there not been a policy of no burning, then up to the whole moorland area might have been burnt over a period of around 18 years. This suggests that while not burning may not stop wildfires occurring, but neither does it necessarily result in widespread wildfires. Nevertheless, depending on site characteristics, including habitat type, it *may* lead to increased fuel load and hence hazard (though see paras.8.4 and 8.7 on managing fuel load). The effects of such an approach seem likely to vary between habitats, sites and areas/regions depending on a range of factors including habitat/vegetation type, composition and condition, hydrology, habitat resilience and restoration management, proximity to urban areas and access points/routes, level of visitor pressure, remoteness and hence risk of accidental or deliberate ignition.

Arson

9.40 As noted earlier, strong evidence from recent English wildfire data (2002–18) indicates that, where a broad cause of fire was assigned (3,269 fires), the majority (77%) were classed as deliberate (arson) (paras. 5.6 and 5.34). However, the percentage was much higher in the lowlands (80%) than the uplands (55%). Strong evidence from south Wales indicates that wildfires are associated with public access, with over 90% of ‘grassfires’ recorded within 100 m of a road or public right of way (PROW) and 99% within 500 m of a road or PROW, and with deprivation, with the 20% of most deprived areas in the region nine times more likely to experience wildfires than the 20% least deprived areas (paras. 5.9 and 5.35). Moderate evidence from a linked investigation of community and stakeholder perceptions of wildfire revealed low public awareness of wildfires with only 33% believing that there is a wildfire problem across south Wales and even less (18%) in their local area, though 65% believed that wildfires were deliberately caused (para. 5.36; also see para. 7.6 regarding educational strategies to address fire-starting in south Wales). Corcoran *et al*. (2007) have previously demonstrated a spatial link between areas of deprivation in south Wales and increased wildfire risk.

9.41 Moderate evidence from modelling of wildland arson and autoregressive crime function in the **USA** indicates that economic conditions within given areas have an influence on the level and location of criminal wildfire activity and that patterns of such activity could be used to plan law enforcement preventative action (para. 5.37). Forest management activity can both reduce and encourage wildland arson activity. Linked to this, moderate evidence indicates temporal and spatial patterns of arson in response to long- and short-term drivers, with explanatory variables including factors associated with economic conditions and level of law enforcement. Arson was considered predictable over short and long timespans as its rate was heavily influenced by weather, climate, fuels and information on other nearby and recent arson fires. Moderate evidence from a review of socio-economic modelling of fire incidence with an emphasis on urban residential fires in the **USA** concluded that fire rates are affected by community characteristics, with socio-economic and environmental factors the primary determinants of fire loss, with fire departments a secondary influence (para. 5.38).

Wildfire behaviour and severity

General fire behaviour and severity

9.42 Moderate evidence indicates that fuel load and vegetation structure, and hence vegetation and habitat type (though most UK evidence relates to *Calluna*-dominated vegetation), are critical factors in fire behaviour in UK heathlands and peatlands, particularly in fireline intensity and rate of spread, although residence time and depth of penetration of lethal temperatures into the soil are also important in determining severity but are less well understood (para. 6.5). There is also moderate evidence that fire behaviour in *Calluna*-dominated heathland and peatland vegetation in the UK is determined by wind speed, though this interacts with vegetation structure and fuel load, which are influenced by *Calluna* growth phase (para. 6.6). This interaction may vary between habitats and time of year.

9.43 As mentioned earlier (para.4.20a), there is moderate evidence that drought or water deficit in *Calluna* provides conditions for an increased rate of spread and intensity of fire in the UK and that that physiological drought may be caused by cold clear weather and frozen ground, and winter cuticle damage, which can reduce the fuel moisture content of live biomass and create the potential for ignition, increased rate of spread and extreme fire behaviour, particularly in spring (para.6.6). This may coincide with the peak period of managed burning in the uplands in spring (para. 5.29). Moderate evidence indicates that critical differences in burn severity and fuel consumption are linked to the flammability of ground fuel layers including bryophytes and litter in UK heathland and peatland (para. 6.7)

9.44 Most of the above evidence is based on *Calluna*-dominated UK heaths and bogs and there appears to be limited evidence on fire behaviour and severity from other vegetation types which are widespread in the uplands and lowlands and are affected by wildfires (paras. 4.21 and 6.9), including other dwarf-shrub and gorse *Ulex* spp. dominated heaths and bogs, graminoid-dominated heaths, bogs, fens and grasslands, especially by *Molinia* and *Eriophorum* spp., and less-modified, *Sphagnum* bog-moss-dominated bogs and fens, and other bryophyte-dominated habitats.

9.45 There is similar, consistent evidence available for some similar non-UK, open habitats, for example, moderate evidence that live-fuel moisture content, shrub-layer density, presence of litter and wind, and the amount and continuity of the dead elevated fuel all influence the sustainability of fire spread in **Australian** shrubland (para. 6.10).

Vegetation and habitat types

9.46 Moderate evidence indicates that fire severity (including ground fuel consumption, ground heating and changes in post-fire soil thermal dynamics) varies by habitat/vegetation type in the UK and elsewhere, for example, **Canada** (para. 6.12). This includes moderate evidence that in the UK, *Calluna*, dry heath and tree dominated sites suffer more severe burning than bog, flushes/fens and bog woodland and that fires on **Canadian** peatlands became more severe following a shift from moderate-rich fen to forested bogs as a result of climate change.

9.47 Moderate evidence indicates that fire spread in **Spanish** shrubland is facilitated by land use/cover types with a high fuel load and homogenous terrain, and by low fuel moisture, with the fire intensity of mature *Ulex* shrub as high as the maximum intensity recommended for prescribed fires (para. 6.13). In the UK, especially where *Ulex europaeus* scrub occurs in discrete blocks on heathland, the upland fringe and in enclosed grasslands, burning is often used for management of mature stands, though it can result in intense, unpredictable fires with a risk them getting out of control, and mechanical treatment is generally recommended as an alternative treatment especially for more extensive stands (e.g. Symes & Day 2003). Such burns can result in accidental wildfires and *U. europaeus* stands are also sometimes deliberately targeted for firesetting (Jenner 2017).

Wildfire prevention

Education, and cultural and community attitudes

9.48 There appears to be little information on the implementation and particularly the effectiveness of education and training strategies in relation to wildfire prevention in the UK, though a number of such projects have been established particularly on the urban-rural fringe, especially adjacent to lowland heathlands (para. 7.5). However, there is moderate evidence that proactive and reactive education measures used by the Forestry Commission Wales and partners in south Wales can reduce the incidence of wildfire arson (para. 7.6). This included community projects such as the ‘Bernie Project’ in Mid-Rhondda, which used ‘social marketing’ techniques to target teenagers over a six-week period which resulted in a relative decrease of 46% (compared with a nearby control) in the number of vegetation wildfires over the period of the intervention which continued for some time afterwards.

9.49 Moderate evidence, especially from **North America** and the **Mediterranean**, indicates that cultural shifts, such as greater awareness of wildfire issues, and the development of community experience and a common vision through education, public participation, may reduce the incidence of wildfire ignitions and, through consensus, lead to the acceptance of the need for actions to reduce the incidence of human-induced fires (para. 7.7).

Habitat restoration

9.50 Restoration of moorland habitats, in particular peatlands, including through rewetting, has been recommended to reduce risk of, and increase resilience to, wildfire in the UK, as well as for wider benefits, and there is moderate evidence that the severity and perhaps incidence of wildfires may be reduced when wetter conditions, in particular high water tables, are maintained or restored (para. 7.8). Similar moderate evidence indicates that fire effects, including ground fuel consumption, ground heating and changes in post-fire soil thermal dynamics, were stronger on a UK dry heath compared to a raised bog (para. 7.9) which is consistent with the likely benefits of rewetting modified bog and fen habitats. In the medium- to longer-term, rewetting is likely to produce changes in sward composition and reduce dominance of more flammable species such as *Calluna* that may pose a wildfire hazard. Other treatments, such as cutting/mowing and appropriate/restoration grazing, may also offer similar benefits in diversifying swards and reducing over-dominance of certain species, including more flammable species such as *Calluna* and *Molinia* (e.g. Critchley *et al*. 2007, Martin *et al*. 2013, Glaves 2016 and Garnett *et al*. 2019) and hence potentially in reducing wildfire risk and severity, and increasing resilience to wildfire, more widely across heathland, peatland and grassland habitats, though there is currently more limited evidence on this specifically in relation to wildfire.

Wildfire management planning

9.51 Wildfire management planning is accepted good practice and, for example, together with risk assessment, is a requirement under Countryside Stewardship agri-environment agreements with lowland heathland and moorland options. In part to address this requirement, the Uplands Management Group has recently produced guidance on Moorland wildfire risk assessment and management planning on behalf of Defra (Uplands Management Group 2019, para. 7.10, Appendix 12). This covers Wildfire Risk Assessment (WRA) including a Wildfire Risk Scoresheet (WRS), Wildfire Response Plans (WRP) and Wildfire Management Plans (WMP). The Forestry Commission's guide on Building resilience into forest management planning provides guidance on managing vegetation and fuels for land managers in forestry and associated open habitats which includes vegetation management (forestry operations and mechanical cutting), grazing and burning using a matrix linked to Wildfire Management Zones to ensure a proportionate approach a both site and landscape scales (Forestry Commission 2014 and Appendix 7).

Firebreaks

9.52 Though detailed guidance on the location and design of firebreaks is available, particularly from the Forestry Commission (2014, paras. 7.15 and 7.16), and their use is widely recommended, for example, by Shaw *et al*. (1996 [3+]), little evidence was identified specifically on the effectiveness of firebreaks for reducing the occurrence and spread of wildfires in the UK (though see para 8.11 regarding their use in relation to fire suppression). Operational proactive strategies used by Forestry Commission Wales include 'designing in' firebreaks in forest planning that can help tackle the spread of large-scale forest fires, though this has apparently been given less emphasis recently within the planning process and there appears to be little information about its effectiveness.

9.53 **Away from the UK**, firebreaks are more widely used and there is moderate evidence that they can be effective in certain situations and conditions, with vegetation type and structure/height, weather conditions, especially wind speed, and seasons being important factors, though effectiveness also depends on firebreak characteristics, especially width, and they tend to become less effective or ineffective in more extreme conditions (para. 7.18).

The Met Office Fire Severity Index and closing and managing access

9.54 The Met Office Fire Severity Index (MOFSI) is based on the Fire Weather Index (FWI) component of the Canadian Forest Fire Danger Rating System (CF FDRS) and provides daily operational mapping of potential fire severity across England and Wales. It uses a simple thresholding of the FSI on a 1 to 5 scale with Level 5 representing 'exceptional' conditions when, *if a fire occurs*, it is likely to be extremely difficult to control (para. 7.21). It does not provide an assessment of the risk of wildfires actually occurring. The MOFSI provides a trigger for fire prevention restrictions on open access land mapped under the CROW Act (2000) which aim to minimise accidental fires on access land vulnerable to wildfires by suspending open access rights when conditions become 'exceptional' (para. 7.25).

9.55 A UK Daily Hazard Assessment (DHA) also provides an 'at a glance' mapped overview of 21 potential natural hazards and health implications that could affect the UK over the following five days, including wildfire (paras. 7.27–7.28). The DHA is informed by the sub-indices of the MOFSI. Whilst the MOFSI and DHA use the same meteorological model, the assessment outputs are for different purposes and are currently presented in very different ways. There may though be scope to consider whether the two systems can be aligned in a way that would fulfil the need to determine when CROW Act restrictions should be in place and also provide an assessment on the likely occurrence and severity of wildfires that can be used more generally by government and emergency responders.

Prediction of extreme fire weather conditions

9.56 Moderate evidence indicates that the MOFSI and the Canadian Fire Weather Index (FWI) on which it is based, in particular the Fuel Moisture Code (FMC) and Initial Spread Index (ISI) components, successfully predict extreme fire weather conditions in the UK which may give rise to particularly severe wildfires should they occur, but that it is less successful in predicting when fires actually occur, especially in the recorded spring peak period (para. 4.15), though this is not the objective of the MOFSI.

9.57 There is moderate evidence from a Met Office review of the performance of the operational MOFSI in 2018, a peak wildfire year in England and Wales (para. 7.30a-c), that:

a. There was a strong correlation between the FWI derived from the operational MOFSI model and an equivalent observation-driven model for seven weather stations selected to represent a range of conditions across England and Wales. The occurrence of severe fire weather was well predicted by the forecast model, though a small negative bias in the operational FWI compared to the version driven by site observations was identified at some sites, though this had no impact on Level 5 ('exceptional') being reached at any of the sites.

b. Levels of MOFSI indices in relation to the location and timing of six notable wildfire incidents showing that "elevated [but not 'exceptional'] fire weather conditions contributed to the severity of the incidents"; on the day of the fires, the MOFSI was at Level 4 (very high) at one site, Level 3 (high) at three sites and Level 2 (moderate) at one. The hot, dry conditions led to a steadily increasing Build-Up Index (BUI) from mid-June to mid-July and particularly severe conditions occurred on windier days when the Initial Spread Index (ISI) was elevated. Though Level 5 was not reached at any of the major event locations, the duration of high FSI values is likely to have contributed to the severity of the wildfire conditions experienced.

c. High levels of fire weather severity (MOFSI Levels 3 and 4) being widespread across England and Wales during the summer of 2018 which were sustained over a duration of several weeks due to a period of hot, dry weather, though MOFSI Level 5 was reached on only four days, over small areas of East Anglia and SE England. Lower relative humidity or stronger winds would have been required to trigger 'exceptional' conditions more widely.

Potential refinements and developments

9.58 There is interest in refining the MOFSI and/or developing a wider Fire Danger Rating System (FDRS) with a number of initiatives in place to develop the latter for the UK or parts of it (para. 7.31). A series of studies summarised by five supporting evidence statements provide evidence that there is scope to refine elements of the FWI to better reflect vegetation types, key species and conditions in the UK, and/or potentially to input to the development of a UK FDRS (para. 7.31a-e). This includes moderate evidence that the fuel moisture indices do not relate strongly to observed changes in live or dead *Calluna* fuel moisture, though further research on fuel moisture dynamics may provide substantial improvements to the fuel Moisture Code and Initial Spread Index for UK conditions and habitats (para. 7.31a). The moisture status of ground fuel layers is a critical control on burn severity in peatlands, which suggests that certain components of the FWI System may be useful in forecasting potential fire severity (para. 7.31b). There is also strong evidence that an alternative percentile-based calibration of FWI components optimised for UK conditions offers significant advantages for classifying UK fire danger that could usefully contribute to future development of MOFSI, DHA or a new FDRS (para. 7.31c).

9.59 There is also moderate evidence that an alternative model which calculates a shrub fire index more accurately predicts the prevalence of fires in spring in the UK uplands and the secondary peak in the summer, and could therefore contribute to the future development of a fire prediction system (FDRS) designed specifically for British conditions (para. 7.31d), though this is not an objective of the current MOFSI.

Use to close access and other potential actions

9.60 No evidence was identified on the effectiveness of closing or managing access at times of 'exceptional' or high risk in the UK in terms of reducing wildfire occurrence (para. 7.32), though open access land can be closed under the CROW Act (paras. 7.23–7.26). The 'exceptional' threshold level of the MOFSI is occasionally met (e.g., on four days in 2018, para. 7.30c), though this does not necessarily overlap with areas of CROW access land identified as vulnerable to wildfire where 'outline directions' may be in place. Closure only covers open access land and does not apply to public rights of way or other access agreements and a possible downside of closing access is that it may risk reduced or slower identification and reporting of wildfires. The last time that fire prevention exclusions were activated on CROW access land was during May 2011, when 32 fire prevention restrictions were activated covering a total area of just over 112,000 ha (para.7.32). There is potential for the FSI level ratings (or a new FDRS) to be used to target and trigger other voluntary interventions on open access, and potentially other, land, such as publicity, including advisory and warning signage about fire risk, management of access short of closure and potentially voluntary restriction of management that may pose a risk, such as managed burning (Glaves *et al*. 2005).

Fire watching

9.61 Although fire watching has been advocated for use in the UK, particularly at wildfire 'hot spots' in the Peak District, little specific evidence was identified from the UK on its use and effectiveness in preventing, or reducing the impact of, wildfires. There is, however, moderate evidence from the Peak District, UK, that resources and interventions that support a rapid, reliable and effective response to a wildfire including fire watching, and improved vehicle access and provision of emergency ponds may show a high return on investment in terms of fire rescue resources saved, even if dedicated personnel and equipment are seldom used (para. 7.38). Only limited evidence was found on fire watching networks being put in place in the UK, though they are widely used elsewhere particularly in remote and forested areas where it is important to initiate a rapid response (para. 7.37).

9.62 In Catalonia, **Spain**, ignition control and extinction represents the most important wildfire management option and accordingly, a network of observers is deployed every summer to report any seat of fire (para. 7.39). The campaign covers a four-month period from June to September, months that encompass 60% of forest fires and 95% of lightning-induced wildfires, though little evidence was provided on its effectiveness in preventing or reducing the impact of wildfires.

Reducing the impact of wildfires

Managing fuel load

9.63 Whilst monitoring and managing fuel load is often advocated in the UK, especially for upland heathland and peatland habitats (e.g. McMorrow & Lindley 2006 [2+], Albertson *et al*. 2010 [2+] and Marrs *et al.* 2018 [2+]), there appears to be limited evidence of its direct effect on wildfire incidence, behaviour, severity and extent, or in reducing wider negative impacts (para. 8.4) which is consistent with the finding of Glaves *et. al*. (2013) with respect to the relationship between managed burning and wildfire. This may in part reflect the relatively short, but increasing, IRS wildfire data set timescale and limited availability of mapped data on managed/prescribed burning especially at a local scale, though periodic mapping is available at a national/upland area scale from remote sensing/earth observation studies (e.g., Yallop *et al*. 2005, Douglas *et al*. 2015, Thacker *et al*. 2015 and Dixon & Chandler 2019) and Natural England is trialling routine operational mapping of burning in the uplands. This might make quantitative analysis of the relationship between burning and wildfires more practical in future. Where carried out in the UK, managing fuel load is mostly done by managed burning (rather than by mechanical treatments, especially cutting/mowing which is increasing on moorland, or grazing and herbicide use), principally for other objectives, particularly game (red grouse) and livestock management (e.g. Defra 2007, Douglas *et al*. 2015; also see paras. 5.29 and 5.30), though fuel reduction may be a potential co-benefit.

9.64 Such burning is a contentious issue (e.g. Douglas *et al*. 2015, 2016, Davies *et al*. 2016 and IUCN 2017), particularly on peatland habitats where it is widely considered to have negative effects on habitat composition, structure and function (e.g. Glaves *et al.* 2013, Brown *et al*. 2014, Lindsay *et al*. 2014 and Natural England 2019) and has been increasing in extent (Douglas *et al*. 2015 and Thacker *et al*. 2015). For example, over the same 2009–2017 period as the IRS wildfire data, a total of *c.*66,000 ha of managed/prescribed burning was recorded on *Calluna*-dominated upland heath and bog in England by Thacker *et al*. (2015) who considered this to be an underestimate (due to some *Calluna*-dominated moorland areas not being included and burns on graminoid-dominated moorland vegetation not being assessed). This compares with a total of *c.*9,500 ha affected by wildfire in the English uplands (moorland >250 m) over the same period based on the published IRS data (para. 4.27), though there may be some differences in the precise upland area included in the these two studies. There may also be differences between managed/prescribed burns and wildfires in terms of severity and impact, and other factors such as distribution and costs/resources for firefighting/ suppression and restoration also need to be considered. Hence there may be trade-offs between different costs and benefits (also see para. 9.68).

9.65 The Forestry Commission's Practice Guide on *Building resilience into forest management planning* provides guidance on managing vegetation and fuels for land managers in forestry and associated open habitats which includes vegetation management (forestry operations and mechanical cutting), grazing and burning using a matrix linked to Wildfire Management Zones to ensure a proportionate approach at both site and landscape scales (Forestry Commission 2014, para. 8.5).

9.66 Managing fuel load by mechanical treatments and prescribed burning is widely practiced elsewhere in the world, particularly in shrub and forest habitats in southern **Europe**, **North America** and **Australia**, and there is strong, but in some specific respects contradictory, evidence that this can be beneficial in reducing hazard and hence the incidence, intensity, severity and extent of wildfires, and in facilitating fire suppression efforts. However, the magnitude and length of the effect, and the cost/benefit ratio, trade-offs and difficulty of implementation vary between sites, habitats, and wider landscapes including at the interface with habitation (para. 8.6). Operational, social, ecological and wider environmental issues and objectives may constrain fuel load management. However, there appears to be less extensive empirical (rather than modelling and theoretical) evidence on these effects. More generally, it has been suggested that there remain considerable apparently unresolved questions over the effects of fuel load management, in particular in relation to the spatial arrangement, size, extent and type of fuel treatments (para. 8.7). As a result, it has been suggested that “the conclusions that can be drawn from these approaches are limited, highlighting the need for more, properly designed experiments addressing [the] question [of fuel treatment effects]”.

9.67 This includes moderate supporting evidence from six evidence statements mostly from shrub and forests, and in some case grassland, habitats, especially from southern **Europe**, **North America** and **Australia**, that the effectiveness of fuel treatments, especially prescribed burning, in reducing the area affected by, and intensity and severity of, subsequent wildfires is influenced by a range of factors (para. 8.7a-f). These include that:

a. Relatively rapid fuel accumulation and limit effectiveness to a relatively short post-treatment period, often as short as a few years in more open habitats. This may in part reflect the re-establishment of fuel continuity (para. 6.10).

b. Spatial pattern, size, shape and continuity of prescribed burning influences its effectiveness in reducing the area affected by subsequent wildfires.

c. Simulations suggest that long linear, especially gridded treated (burnt/cut) ‘barriers’ are more likely to be effective than patches (though gaps lead to reductions in effectiveness).

d. Relatively high proportions of an area are likely to be required to be subject to burning annually to have an effect on the area affected by subsequent wildfire, though this can result in as much or more being subject to burning (prescribed and wildfire) in total and/or the treated area exceeding the reduction in area of wildfire.

e. Treatment level (proportion up to 50% area per annum) has the greatest influence in modifying fire effects, whereas treatment unit size has the least.

f. Other factors, in particular variation in weather (probably becoming more important in areas with greater variability), and success of ‘ignition management’ (prevention), may also be important, or more important, in explaining variation in area burned by wildfire than fuel management approach and effort.

g. The best results of prescribed fire application are likely to be attained in heterogeneous landscapes and in climates where the likelihood of extreme weather conditions is low; treatment is not efficient in degraded ecological states dominated by invasive plants.

h. “Optimisation of the spatial pattern of fire application is critical but has been poorly addressed by research and practical management guidelines are lacking to initiate this”.

9.68 These effects were described from non-UK studies, and are likely to vary geographically, and between sites and habitats. Where managed burning occurs on heathlands and peatlands in the UK, it tends to be done for other purposes and, particularly on grouse moors, involves the creation of an extensive patchwork of small blocks (median 0.25–0.28 ha, Yallop *et al*. 2005), managed on short or moderate (e.g., 10–20+ year) rotations. The above findings suggest that such burning *might* not necessarily provide the most effective spatial pattern, frequency or approach specifically for reducing wildfire risk, occurrence and impact. Where this is an objective, a more strategic approach targeted at high risk locations such as access hotspots/routes, probably with more frequent and varied treatments, *might* be more effective and efficient, and potentially also result in a smaller total area being burnt. However, as noted previously, severity and impact also need to be considered and more evidence is required on the effects of different burn patch/strip configurations in a UK setting. Nevertheless, targeted fuel management may contribute to an Integrated Fire Management approach (e.g., Silva *et al.* 2010). Fuel management and particularly the creation of firebreaks, may also provide vehicle access and hence can assist fire suppression when a wildfire occurs. However, there may be other trade-offs, particularly in relation to peatlands, not just in terms of the area affected compared to fire severity and impact, but potentially other factors such as burn frequency, with some areas repeatedly burnt on rotation (with a cumulative effect) compared to likely longer return periods and perhaps a less concentrated, more widespread geographic distribution of wildfires (e.g. at a regional scale, para. 4.14). Managed burning may also have other effects, for example, there is some evidence from a recent study that recently burnt areas were more severely affected by a subsequent wildfire, resulting, for example, in greater bare ground cover (Swindell 2017). Such differences between managed burning and wildfires, including scale, may result in different effects on habitat structure and function, and associated ecosystem services.

Natural fire regimes

9.69 There is moderate evidence internationally that ‘natural’, or more natural, fire regimes, without complete fire suppression, can result in landscapes that are more self-regulating and resilient to wildfire (para. 8.8). This may perhaps be more relevant to more natural, less modified and more extensive, remote areas and regions, and hence perhaps be less applicable to much of the UK, especially England. It does, though, raise a question over what is the UK’s natural (and indeed historical) fire regime, bearing in mind that lightning-induced natural fires are rare, and whether it is seen anywhere currently. Related to this, is the extent to which British plant species and communities are fire adapted.

Fire suppression/firefighting

9.70 There is moderate evidence from the Peak District that resources and interventions that support a rapid, reliable and effective response to a wildfire such as fire watching, improved vehicle access and provision of emergency ponds may show a high return on investment in terms of fire rescue resources saved, even if dedicated personnel and equipment are seldom used (para. 8.10).

9.71 Forestry Commission fire control trials provide strong evidence that back fire, flanks and fire head were effectively suppressed in *Calluna* stands, though in *Molinia* fires only the back fire and flanks were suppressed because the head fires moved very quickly and were confined by firebreaks (para. 8.11). In some test conditions, greater fire intensities were experienced with small fuel loads with a fast rate of spread (ROS), compared to fires with large fuel loads with a slow ROS. With waterless suppression using belt and wire-mesh beaters, a conveyor belt head was best in *Molinia* fires, whereas in *Calluna* fires long-handled wire mesh beaters were most effective. Water suppression was tested using high-pressure portable pumps and very high pressure (low volume) pumps each using jet stream, spray and fog patterns, and the combined use of a fogging system and a team of beater operators was found to be the most efficient fire suppression method in both *Molinia* and *Calluna* fires.

Conclusions

9.72 There are differences in the quantity and quality of evidence and hence number and strength of evidence statements between the review questions. There was a considerable volume of mostly strong and moderate evidence statements on wildfire risk and occurrence, and ignition sources, but more limited, mostly moderate evidence on fire behaviour and severity, prevention and reducing impact (para. 9.3 and Table 6). Nevertheless, overall the volume and quality of evidence evaluated in this review has been sufficient to enable the synthesis of a series of evidence statements that describe the current state of knowledge on the occurrence, causes, prevention and management of wildfires on open, semi-natural habitats in the UK, particularly on heathlands and peatlands in England. The evidence is summarised and to a limited extent interpreted above, specifically in relation to the individual review questions, and below more briefly in terms of the overall key findings and conclusions across the questions.

9.73 Wildfires can and do occur across the country and on all the main terrestrial habitats, but, by area, particularly on upland and lowland heathlands, and peatlands. In the uplands, most wildfires occur in spring, except in extreme fire years when periodic summer fires may be more frequent. In the lowlands, where the number of fires is much higher, a spring peak is still evident, though fires are more evenly spread over spring and summer. Although large wildfires are associated with the uplands, they also occur in the lowlands, particularly on heathland. Data from the IRS for wildfires attended by the FRS indicate that a total of *c*.35,500 ha was affected by wildfire over eight recent years (to 2016/17) with a mean of *c*.4,400 ha/year, though there was much variation between years. The majority by area was on open, semi-natural habitats (59%), especially ‘mountain, heath and bog’ (48%). Whilst this represents a considerable area over a relatively short period (with a cumulatively larger area likely to be affected over longer time periods), it is, however, a small proportion of the total area of open, semi-natural habitat in England. Nevertheless, the area affected increases cumulatively over time as post-fire recovery can be slow, and wildfire frequency and magnitude are considered likely to increase in response to climate change.

9.74 Natural wildfires due to lightning strikes are rare in the UK and most wildfires are the result of human action, through either arson or accident. There is geographical variation in the relative importance of different causes of wildfire. Arson is more frequent in the lowlands and in urban and urban-rural-fringe areas, whilst the proportion of accidental fires is higher in the uplands and probably in more rural areas in general. They tend to be associated with public access and recreation, with the majority of accidental wildfires resulting from 'camp' and other fires, especially in the lowlands, though land management burns getting out of control are also a significant cause in the uplands.

9.75 Risk and occurrence of wildfire in the UK is associated with hot, dry weather conditions, especially drought (or, particularly in spring, low temperatures and frozen conditions), particular vegetation characteristics (including plant functional type, autecology, phenology, age/growth stage and height/structure, (high) fuel load and fuel structure, and (low) moisture content) and human-related accidental ignition associated with public access, recent or current wildfire and managed burning activity, and arson. These factors also affect fire behaviour, severity and extent, and are also likely to affect impact (though the last is beyond the scope of this review).

9.76 The incidence of wildfire, especially large wildfires is episodic, coinciding as mentioned with dry-spells, especially drought, hot periods and heatwaves, with much variation between years which makes determination of temporal trends difficult, especially as systematic collation of wildfire data nationally is relatively recent, though data to date show little evidence of clear trends. Nevertheless, the UK IRS database and the recent FC analysis of it for England provides the most comprehensive data available on wildfire occurrence and its value will increase over time as more information is added annually. There is scope for more detailed, and additional, information to be collected through the IRS and/or other wildfire recording schemes, particularly on the cause of individual wildfires. This could then be usefully related to other geographical data sets on factors that may influence wildfire occurrence and its effects, including more detailed classification of habitat types affected.

9.77 Limited evidence was identified on the effectiveness of managing access and behaviour to reduce wildfire risk and occurrence, especially in the UK, though some partnership and community wildfire initiatives have recently been established that address these issues, including through targeted education. Evidence from one such project in south Wales indicates that proactive and reactive education measures can reduce the incidence of wildfire arson. The MOFSI is generally effective in predicting 'exceptional' conditions when very severe fires are likely, *should they start*, but there is little evidence on the effectiveness of closure of open access land on wildfire occurrence and severity. The MOFSI does not predict wildfire risk or occurrence, but there is growing interest in developing a full FDRS for the UK and/or parts of it.

9.78 Limited evidence was identified specifically on the effectiveness of other wildfire prevention measures and management to reduce wildfire impacts in the UK, though more evidence and experience in relation to this may be held by practitioners (some of which may have fed into the concurrent Defra review). For at least some of these interventions, for example fuel management, effectiveness may be influenced by factors such as its scale, pattern and frequency, and the use of strategic targeting in relation to risk factors. These factors may also influence wider effects, including on ecosystem services, and result in potential trade-offs between delivery of different objectives and outcomes. Habitat restoration, particularly of peatlands, as well as delivering wider benefits may offer the opportunity to reduce risk and increase resilience to wildfire and other impacts, and potentially address over-dominance of more flammable species, though limited existing evidence was identified on this specifically in relation to wildfire occurrence and impact, but it is subject to ongoing study.

9.79 Despite differences in the quantity and quality of evidence between the review questions, the review has summarised the available evidence on the occurrence, causes, prevention and management of wildfires in England enabling the identification of evidence gaps and the research recommendations listed below.

Research recommendations

9.80 Assessment of the available evidence reviewed and summarised above, and in the previous evidence sections (4–8) which give research recommendations in relation to each of the eight individual review questions, highlights evidence gaps which suggest that the following issues would benefit from further research, monitoring or other investigation. Most relate to England, though at least some may be appropriate at a wider UK level (with the report sections and questions they most directly relate to given in brackets at the end of each issue):

Data on wildfire occurrence and related factors (IRS and other datasets)

a. Where possible, standardisation of the range of variables recorded and definitions used, particularly cause of ignition, between the Home Office's national Incident Recording Scheme (IRS) and other wildfire recording schemes to enable compatibility of data nationally. (Sections 4, 5; Questions 1, 2.)

b. Improved recording of wildfires not attended by the Fire and Rescue Service (FRS), and hence not included in the IRS, using new or existing recording systems, for example those maintained by Natural England and the MOD. (Some such fires are believed to be included in Natural England's wildfire database, so there may by scope to get an indication of the number and extent of these by assessing the proportion of fires in the database included in the IRS, at least for heathland, peatland and other open, semi-natural habitats/land cover types.) (Sections 4, 5; Questions 1, 2.)

c. Extension of the main analyses done so far using the IRS to further explore the occurrence of wildfire in England and potentially the rest of GB/UK, and factors that may influence this and its severity, extent and impact. Specifically, this should include the timing (e.g., weekly/monthly/seasonally), cause (ideally using agreed definitions/ classification and determination of area burnt as a result of different ignition sources), and specific habitat (e.g., using Natural England's Priority Habitat Inventory) and land use types affected. (Sections 4, 5; Questions 1, 2.)

Further analyses/modelling using additional data sets or new data

d. Further exploration, and potentially modelling, of factors associated with the occurrence of wildfires using the IRS and additional data sets held by government (e.g., MOD and Natural England) and other organisations. (Sections 4, 5; Questions 1, 2.)

e. Wider exploration of the effect of weather events and climate on wildfire occurrence and extent using existing weather, climate and wildfire data. (Section 4, 5; Questions 1, 2.)

f. Review and extension of the potential use of Earth Observation data to improve wildfire mapping and characterisation (e.g., of severity, Schepers *et al*. 2014 and Scottish Natural Heritage 2018), perhaps linked to existing GIS data sets. This could assist in addressing other recommendations regarding occurrence, severity, extent and impact, particularly those above. (Sections 4, 5; Questions 1, 2.)

Socio-economic aspects

g. Incorporation of socio-economic aspects in consideration of monitoring and research on wildfire occurrence, severity, extent and impact, and in wildfire prevention and management/control (reducing impact). This could be done separately or ideally integrated with biophysical research, but in either case, the findings ought to be interpreted holistically. It should involve engagement with the wildfire community, other stakeholders, land managers and the public. (Sections 4, 5, 7, 8; Questions 1, 2, 4, 6, 8.)

Relationship between managed burning and wildfire

h. Investigation of the relationship between routine managed burning and prescribed burning (and cutting/mowing and other management with a fuel management objective) and wildfire occurrence, extent, and ideally severity and impact. This should consider the potentially beneficial effect of fuel management and how factors such as the scale, pattern frequency and targeting (in relation to risk factors) affect this, and the effect of burns escaping control resulting in wildfires and the factors that contribute to and cause loss of control. The latter may include consideration of indirect effects such as effects of managed/prescribed burns on vegetation composition (e.g., dominance of more flammable species/vegetation types) and water table (lowering). (Sections 4, 5, 8; Questions 1, 2, 8.)

i. Linked to (h) above, investigation, potentially involving modelling, of the most effective burn configuration (patch size, shape, pattern, scale, frequency) and targeting of managed/prescribed burning to manage fuel load to reduce wildfire occurrence, severity, extent and impact. This would need to consider habitat/vegetation type and composition, including types other than just *Calluna*-dominated vegetation. (Section 8, Question 8.)

j. Extension of recording/mapping of managed/prescribed burning in England potentially using Earth Observation, particularly in the uplands, in part to contribute towards investigation of the relationship with wildfire occurrence. (Sections 4, 5, 8; Questions 1, 2, 8.)

k. Similar to (h) above and potentially linked to restoration (w) below, carry out a broader investigation of the effects of wider management interventions, e.g., grazing, scrub and bracken management, and drainage, on wildfire occurrence, severity, extent and impact. (Sections 4, 5, 8; Questions 1, 2, 8.)

Prosecutions

l. Collation nationally of details on any prosecutions that arise as a result of wildfires (for arson and if possible for breaches of the Heather and Grass Burning Regulations) to allow identification of common issues. (Section 5, Question 2.)

Fire behavior, severity and impact

m. Extension of research into fire behaviour, fuel moisture dynamics, severity, extent and impact, especially in non-*Calluna*-dominated vegetation, and across habitat transitions, potentially including to forestry/woodland and the urban-fringe, in part to input to future development of a full FDRS. (Sections 6, 7; Questions 3, 6.)

n. In reviewing factors associated with wildfire impact (e.g., (d) above), potential impact should also be considered. This could include assessments of, and inputs to risk registers, and tools developed for wildfire management planning including risk assessment, scoring and mapping and fuel mapping. (Sections 4, 5, 6; Questions 1, 2, 3, 4, 5, 6, 7, 8.)

o. Development of an approach to recording burn severity using a simple on-the-ground method of assessment, potentially for use in wildfire recording schemes, and/or based on Earth Observation (e.g., Schepers *et al*. 2014 and Scottish Natural Heritage 2018). (Sections 4, 6; Questions 1, 3.)

Prevention and suppression

p. Further research on the design and effectiveness of fire and fuel breaks, and fire suppression in open habitats (and forestry). (Sections 7, 8; Questions 5, 8.)

q. An investigation with the Met Office to consider the technical feasibility of aligning the wildfire component of the Daily Hazard Assessment with the Fire Severity Index and the potential for the DHA to provide a trigger for 'exceptional' conditions instead of the MOFSI. (Section 7, Question 6.)

r. Further investigation of the development of a UK Fire Danger Rating System, including reviewing implementation, engagement/communication and management, and how best to communicate risk warnings to stakeholders, land managers and the public. (Section 7, Question 6.)

s. Exploration of the effectiveness of Wildfire Risk and Fuel Maps and associated guidance, and the role they may have in wildfire prevention and control/management. (Sections 7; 8; Questions 4, 8.)

t. Investigation of the effectiveness of access closure and restrictions, including Access Management Plans, and potentially management restrictions, on wildfire occurrence, severity, extent and impact. (Section 7; Questions 4, 6.)

u. Exploration of the use and effectiveness of fire watching and other (including automated) Early Warning Systems, and when they are best be deployed. (Section 7; Question 7.)

Vegetation, habitat and fire regime

v. Research into the influence of sward composition and structure on the occurrence, severity, extent and impact of wildfire. (Sections 4, 7; Questions 1, 4)

w. Research and monitoring of the effect of peatland and other habitat restoration on wildfire risk/hazard, occurrence, severity, extent and impact, and its effect on habitat resilience (linked to (v) above). (Section 7, Question 4.)

x. Investigation into the natural (and historic) fire regime in the UK (probably involving paleoecological and perhaps restoration/reconstruction ecology studies), its impact upon vegetation communities, including an assessment of the extent to which they are fire-adapted, and hence the implications for the use of fire in managing UK vegetation. (Section 8, Question 8.)

10 References

Part 1. Evaluated references and other submissions

The following references were derived from searches in relation the review questions and wildfire more generally, and from submissions to the review, which were evaluated in order to summarise the evidence base from which the evidence statements given in Sections 4–11 were developed. Not all are quoted in support of the final individual evidence statements but further details on all are given in Appendix 1.

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Part 2. Additional non-evaluated references

The following references were not formally evaluated in the review in relation to the review questions and hence did not contribute to the development of the evidence statements, but were included in the report text to provide context, particularly in the wider Introduction (Section 1) and introductions to individual sections and subsections, and to aid wider interpretation of the findings.

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Appendices

The appendices listed on page ix are available as separate documents.

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