Uplandia: making better policy in complex upland systems. Final report.

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Policy Context

Uplands are a key priority for Defra and Natural England, given their importance for climate change mitigation, biodiversity, drinking water provision, flood risk mitigation, agriculture, recreation and culture. Uplands feature prominently in Defra's 25 year plan and peatlands (many of which are in the English uplands) are being targeted for restoration in the Nature for Climate Fund and forthcoming England Peat Strategy (to be delivered by Natural England), as part of the UK's plans to reach net zero emissions for the land use sector. Linked to this, legislation is now being brought forward to prevent the burning of heather and other vegetation on protected blanket bog habitats. However, little is known about how the cessation of burning (and possible replacement with mechanical cutting) might influence wildfire risk, especially in sites that are not in favourable condition, if these changes in management are not accompanied by restoration measures.

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The Policy Challenge

Uplands are complex social-ecological systems, and policy interventions designed to deliver net zero and biodiversity targets may have unintended effects on other parts of the system, which could inadvertently undermine these and other policy goals. Existing policy appraisal methods based on evidence synthesis are able to show how specific policy interventions (e.g. peatland restoration) are likely to influence specific outcomes (e.g. GHG emissions). However, these methods are not able to explain how different interventions may interact when combined, or predict how multiple outcomes may trade-off with each other, to produce unexpected outcomes. Interpreting conflicting evidence and addressing low strength of evidence with high uncertainty can also limit attempts to inform policy directly.

An evidence-based solution

Systems models enable evidence syntheses to be integrated with each other, alongside other sources of evidence including, for example, computational models and qualitative data. By representing key system components and their linkages, simple Logic Maps or more sophisticated Bayesian Networks enable policy analysts to see how new evidence or different assumptions about contested relationships is likely to influence the outcomes of a policy intervention. By making the complexity of the systems and the decision-makers assumptions explicit, these methods enable more transparent decision-making under conditions of uncertainty.

Our Approach

This project developed a Bayesian Belief Network for English uplands, representing key system components and relationships on the basis of the best available evidence. Given the policy relevance of managed and wild fire, a rapid evidence synthesis was conducted to assess factors influencing the behaviour of peatland users and managers in relation to wildfire, which informed a wildfire sub-model. By considering four scenarios (below), it was possible to consider how changes in the availability of public funding and/or carbon finance might alter the overall utility of uplands and provision of specific ecosystem services.

The Policy scenarios

Public funding for upland management is expected to change significantly as the UK constructs post-Brexit policies. If this leads to a reduction in public funding, this might trigger the abandonment of some uplands or more intensive management where outputs can be produced for the market. Alternatively, ecosystem markets such as the Peatland Code, and emerging instruments (such as Landscape Enterprise Networks or a proposed UK Farm Soil Carbon Code for non-peat uplands), might provide substantial new revenue streams, retaining overall funding levels at or above levels experienced prior to EU-exit.

Key findings from the Uplandia model

- There is a trade-off between maximising productivity and provision of ecosystem services notably climate regulation, flood protection, water quality and biodiversity. This trade-off is robust and resilient to changes in individual interventions and habitat extent or condition. If levels of funding post-Brexit were to trigger more intensive management in some locations for products that have a sufficiently strong market demand, these private goods could come at a significance cost in terms of reduced public goods from these uplands.
- Maximising climate regulation, flood protection and water quality are generally consistent with maximising biodiversity, but spatial and taxonomic heterogeneity, and difficulties valuing biodiversity make trade-offs difficult to predict. To ensure biodiversity is not compromised by future upland policy and regulation, a precautionary approach will be needed, piloting and evaluating interventions in a range of upland contexts before integrating them into a national framework.
- The model allows resilience of specific services or habitats to be explored. For example increasing cover and condition of blanket bog habitats results in a 75% probability of maintaining or increasing climate regulation, flood protection and biodiversity in the context of predicted climate change. In contrast, if cover and condition of this habitat were to decline, there would only be a 57% to 67% probability of maintaining or increasing these services.
- Wildfire reduction potential is decreased under a payment for ecosystem services scenario compared to a maximising productivity scenario largely as a result of changes in fuel type related to habitat extent and connectivity of habitat.

- Sensitivity analysis suggests that wildfire reduction potential could best be retained or enhanced by reducing fire ignition risk, highlighting the importance of effective behavioural change interventions (see findings from the wildfire evidence synthesis below).
- It also indicates that direct interventions to reduce habitat connectivity and fuel load such as mechanical cutting may have an important role to play. Note, that there is considerable uncertainty about how mechanical cutting should be implemented to reduce landscape-scale connectivity; small scale fire-breaks may not be effective.
- The model also indicates that rewetting is also likely to be effective in maintaining wildfire reduction potential in the long-term, as it leads to changes in fuel type, as well as having beneficial effects on other services, notably climate regulation, flood protection, water provisioning and biodiversity.

Key findings from the wildfire evidence synthesis

A rapid evidence assessment [ongoing] identifies factors influencing the behaviour of peatland users and managers, in relation to wildfire (this report summarises interim findings, which will be finalised in April 2021). Social science research relating to wildfire management in UK peatlands (either related to fuel management or ignition behaviours) was limited, so evidence was considered from comparable international peatlands and where potentially relevant, from the wider literature on behaviours related to forest fires in Europe and the USA. In these cases, the difference in environmental context makes it difficult to infer the relevance of findings to a UK peatland context. Despite these evidence gaps and uncertainties, a number of policy-relevant themes can be identified at this stage:

- Based on a global review of prescribed burning practices, there is evidence that the development of **stringent 'command and control' policies and increased regulation of traditional, self-organised fire-based land management systems can have potentially negative impacts for managing wildfire risk. Instead, evidence from prescribed burning in Europe and wildfire management in US forest systems, suggest that flexible policy and planning approaches (and regular review), including regional policy adaptation, can increase the ownership, uptake and sustained application of wildfire mitigation measures, and so reduce wildfire risk.** In European and international contexts, the continuation of traditional land use systems has been identified as important to the retention of sustainable prescribed burning practices over the long-term.Spatial planning including land management plans which incorporate fire risk planning offer potential for enhancing hazard awareness and mitigating wildfire risk. Grazing programmes have been used effectively for managing fuel breaks in some land use contexts (with appropriate incentives and monitoring), and could be explored in the UK context.
- Spatial planning including **land management plans which incorporate fire risk planning offer potential for enhancing hazard awareness and mitigating wildfire risk.** Grazing programs have been used effectively for managing fuel breaks in some land use contexts (with appropriate incentives and monitoring), and could be explored in the UK context.
- The integration of local knowledge and use of trusted local information sources is important to **frame wildfire mitigation messages** for rural communities who are more likely to adopt these where are perceived to align with existing community identity, norms and culture (compared to suburban and rural-urban fringe communities who may be more receptive to more top-

down approaches). For example, public and stakeholder support for a wildfire early warning system in a UK protected area was dependent on the extent to which implementation enabled shared understandings of fire hazards and incorporated pre-existing stakeholder values and dynamics.

- The development of **place specific, collaborative, community wildfire programs** can have positive effects for mitigating wildfire risk at community and landscape levels. These may include, for example, collaborative development of land management plans and training. While the literature emphasizes the need for skills and knowledge to be place-specific, **national training standards and certification** has also been associated with increased uptake of mitigation measures and adoption of best practice. With effective facilitation, community programs may enable resource-pooling and planned collaborative responses to wildfire. This may increase the likelihood of a rapid response to wildfire, and by building a common sense of purpose linked to shared values, may enhance uptake of mitigation measures. In addition, there is also evidence that wildfire preparedness may be greater in more cohesive and connected communities, as community members inform and support decision-making by individual land managers.
- **Public attitudes towards fuel management can affect land manager behaviours relating to burning practices.** Negative public perceptions of prescribed burning was one factor responsible for a decline in this practice in Irish hill farms, and there is evidence from Europe and the USA that effective communication can change public perceptions of the benefits and impacts of prescribed burning.
- Public outreach that: **i) involves citizens (i.e. is interactive/ participative); ii) occurs at all stages (before, during, after fires); iii) uses consistent messaging; iv) employs a tailored placed-based approach for high risk areas; and v) takes a partnership building approach** between agencies and communities, can increase acceptance of the need for fire management and mitigation measures among members of the public and land managers. While the

literature emphasised consistency over time, it also identified the idea of 'teachable moments' immediately after fires timing, during which risk reduction messages may be particularly effective.

- **Police involvement in wildfire awareness campaigns and youth initiatives (and prioritisation of wildfire a**s an issue at local levels by police forces) offers potential for increasing the impact of outreach programmes and reducing wildfire risk. Targeted training courses with young people in high-risk areas of Wales led to a 46% decrease in call outs recorded by the fire service, and a programme involving the police in Dorset led to a 60% decrease in heathland fires in the region.

Behaviours and interventions relating to wildfire ignition (accidental and intentional) identified from the rapid evidence assessment:

Behaviour category	Specific Manager/ User Behaviours	Interventions
Wildfire ignition - accidental	Loss of control of prescribed burns (fire spread)	**Promotion of best practice** (intensity, timing etc.) and sufficient available staff/support and equipment
	Accidental ignition from other user groups (camping, barbecues)	**Public education/engagement on fire risk awareness** responsible fire behaviour/fire risks from accidental ignition (fire risk campaigns etc.
Wildfire ignition - intentional	Arson/intentional fire starting	**Public wildfire education** (on wildfire arson and risks from intentional fire setting) - youth education programmes on wildfire risk/risk awareness
		Targeted education (specific groups) and local awareness and engagement programmes on wildfire risk awareness
		Police involvement in wildfire mitigation strategies and awareness programmes
		Limiting access to high risk areas (visitor management)

Find out more

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1 Introduction

Assessing the linkages between upland management, habitat condition and extent, ecosystem services, and the needs of people is complex. Multiple interactions have downstream impacts that are mediated by drivers operating across different spatio-temporal scales. Important information can be quantitative or qualitative and is often highly uncertain. This poses major challenges for evidence synthesis and evidence-informed policy generation.

We have approached this problem by developing a logic map linking changes in upland management to UK Biodiversity action plan priority habitats and their associated natural capital based on extant [non-systematic] sources. We have then used a combination of literature and expert elicitation to parameterise the strength and certainty of relationships to generate a Bayesian Belief Network. The relative value of the ecosystem services has been incorporated in this network to provide a decision support tool but a full decision theoretic model would require incorporation of costs and spatially explicit information particularly on biodiversity which is problematic to fully value.

Initial analysis illustrates that payments for ecosystem service maximise utility compared to maximising production or market collapse but that services may also be retained where agricultural communities are sustained. It is worth noting in this context, that cultural landscapes often have high biodiversity value and can be consistent with provision of services such as climate regulation and flood mitigation. However, major trade-offs exist between maximising production and other ecosystem services notably climate regulation, water provisioning, flood risk mitigation and biodiversity. Overall systems resilience is high under a payment for ecosystem services scenario as a result of the large number of system interactions and positive impacts across multiple services. Further work is required to ascertain system sensitivity when modelling assumptions are relaxed.

Changes to upland management enhancing climate regulation, flood mitigation, water quality and biodiversity (some elements) may result in decreased potential for landscape level wildfire mitigation. The systems model indicated that ignition source was a key sensitivity along with changes to fuel load resulting from changes in habitat extent and connectivity. Qualitative information from rapid evidence assessment indicated how ignition risks could be reduced by specific behaviour change interventions and broader policy directives. Other drivers could be addressed by increasing emphasis on rewetting of upland habitats and mechanical cutting to manipulate fuel loads and connectivity although the optimal deployment of such interventions, particularly the latter, remains a matter of conjecture.

The combination of evidence synthesis and systems modelling (with propagation of uncertainty) employed in Uplandia has allowed strengthened policy support despite a challenging and diverse evidence-base in a contested policy arena. This has only been possible because of input from a broad range of scientists, modellers, policymakers, and broader stakeholders within the Uplandia team, workshop participants and beyond. I thank everyone who lives, works, plays or studies in the uplands for constructive engagement but especially the friends and collaborators directly involved.

2 The Uplandia Bayesian Belief Network

2.1 Background and aims

As part of the report by Reed et al. (2020) on 'Social barriers and opportunities to the implementation of the England Peat Strategy' to Natural England and Defra, logic maps were produced to provide an analysis of social barriers and opportunities for implementing the England Peat Strategy. Logic mapping is a tool for articulating underlying and implicit assumptions of what changes will occur, the delivery steps which need to be undertaken to achieve the anticipated changes and the external factors which will also influence the outcome (https://www.gov.uk/government/publications/logic-mapping-hints-and-tips-guide). The Logic maps produced in the above report attempted to link land management interventions to habitats/natural capital and the ecosystem services they provide. The aim of this project was to develop a Bayesian Belief Network (BBN) based on these logic maps to demonstrate the use of BBNs as Decision Support Tools for the evaluation of optimal policy options in complex systems.

2.2 Methodology

Bayesian Belief Networks – general introduction

Bayesian Belief Networks (BBNs) are graphical probabilistic models that represent system variables and their conditional relationships as nodes and arcs in a so-called Directed Acyclic Graph (DAG) (i.e., a graph that has no feedback loops). Relationships between system variables are defined using conditional probability distributions (i.e., the probability of an event occurring given that another event has occurred), and BBNs therefore explicitly account for uncertainty and variability in model predictions. BBNs typically operate with discrete probabilities, which means that each node in the BBN is assigned a finite set of mutually exclusive state values and the conditional probabilities between variables are represented by conditional probability tables (CPTs). The construction of a DAG is usually based on a subjective, but scientifically informed, evaluation of the causal links between system variables, whereas CPTs can be built based on various information sources, including empirical data, existing models and/or expert opinion. The ability of BBNs to integrate quantitative and qualitative information is one of the main advantages of the BBN approach. Another major advantage of the BBN approach is that it allows to carry out probabilistic inference based on (uncertain) evidence. Probabilistic inference is simply the task of calculating the posterior probability distribution of the BBN given the available observations and can be both predictive (i.e. reasoning from new observations of causes to new beliefs about the effects) and diagnostic (i.e. reasoning from observed effects to updated beliefs about causes). The general principles of Bayesian networks have been described extensively elsewhere (Korb and Nicholson, 2004) and will not be discussed in detail here.

BBN model development

The first step in developing a BBN is to define the model structure (i.e., the DAG). For the work here, the intention is to use the previously developed logic maps in Reed et al. (2020) as the foundation for the BBN. The logic maps look at how four different post-Brexit economic scenarios and associated management interventions might affect habitats and the ecosystem services they provide. The overall structure of the logic maps is as shown in Figure 2.1. In the following each of the 'layers' in the logic maps are briefly described.

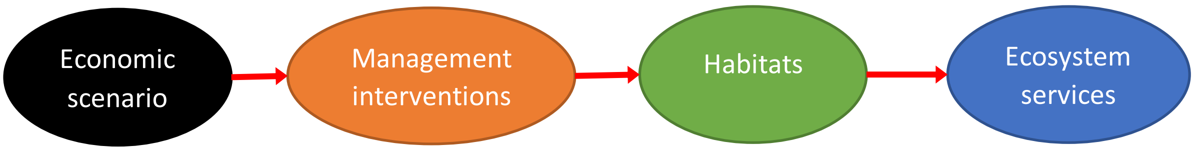

Figure 2.1: Schematic of logic map and the BBN

Economic scenarios

Four alternative futures are considered based on Reed and Young (2017). These are:

1. Maximise production
2. Market collapse
3. Public money for public goods
4. Sustaining agricultural communities

The first two scenarios focus on two very different outcomes of significantly reducing or removing payments to land managers after Brexit, making farming operations in peatlands to depend on the market for their survival. The 'Maximise production' scenario explores a future in which markets can sustain farming in these upland environments and a lower regulatory burden makes more intensive management possible. The 'Market collapse' scenario explores what might happen if markets are not able to sustain farming in these environments, leading to a significant reduction in the intensity of management and land abandonment.

The next two scenarios consider two alternative futures in which payments to land managers are maintained post-Brexit. The 'Public money for public goods' scenario focuses on optimizing public benefits in return for reduced but continued public support, with payments linked to the delivery of public benefits such as climate mitigation and water quality. The 'Sustaining agricultural communities' scenario adopts the same 'public money for public benefits' policy, but retains current funding levels, using this additional funding to protect and sustain rural communities through LEADER style projects, and focusing as much on the economic and social sustainability of rural communities as it does on making payments directly to land managers.

Management interventions and other stressors

The management interventions and other stressors included in the logic maps were adapted from Bunce et al. (2018a) paper on ‘The Ecology of British Upland Landscapes. II. The influence of policy on the current character of the Uplands and the potential for change’. For each economic scenario, expert assessment was applied to determine the most likely trend (‘Y’ – yes/occurs, ‘N’ – no/does not occur, ‘+’ – increase, ‘-‘ – decrease, ‘=’ – no change) in the range of upland interventions and processes.

For the BBN model development, it was initially decided to include the same management interventions and stressors as in Bunce et al. (2018). However, following a review and feedback from the stakeholder workshops, it was decided to remove ‘Rewilding’, ‘Deer management’ and ‘Tree colonisation’ in the BBN as these were deemed to be covered by other management variables already included in the model. It was also decided to include ‘Bog rewetting’, ‘Bog restoration’ and ‘Enhance boundary & linear’ as additional management interventions. Bog rewetting was defined as restoration of degraded bog to a functioning bog, including grip blocking while bog restoration represented bog restoration from other habitats, primarily forestry. Enhance boundary & linear’ includes hedgerow management and restoration. Finally, the variables ‘Grouse – fire’ and ‘Grouse – persecution of wildlife’ included in Bunce et al. (2018a) were renamed as ‘Managed burning’ and ‘Grouse – tracks’ to reflect maintenance and construction of access tracks for grouse management purposes.

Table 2.1 presents an overview of the management interventions included in the BBN. Each management intervention has been assigned 3 possible state values (*increase*, *no change*, and *decrease*) and Table 2.1 shows how the interventions are expected to change for each of the four economic scenarios considered.

Table 2.1: Overview of management interventions included in the BBN and how these are expected to change for the four scenarios considered (increase (+), decrease (-), no change (=) and unknown (?).

	Management interventions	**Market collapse**	**Public money for public goods**	**Maximize production**	**Sustain agricultural communities**
Land management	Sheep grazing intensity	-	-	+	+
	Cattle grazing intensity	-	+	+	+
	Pesticide/herbicide	-	?	+	=
	Artificial fertilizer	-	-	+	=
	Silage	-	?	+	=
	Hay	-	+	-	-
	Drainage	-	-	+	=
Game management	Managed burning	-	-	+	=
	Grouse – tracks	-	-	+	=
	Deer overgrazing	+	-	-	-
Afforestation	Planting of conifer	+	+	+	=
	Planting of broadleaf	-	+	-	=
Conservation	Landscape protection	-	+	-	+
	Bog restoration	+	+	-	+
	Bog re-wetting	+	+	-	+
	Enhance boundary & linear	=	+	-	+

Urbanisation	Mass events	-	+	+	+
	Recreation	-	+	+	=
	New buildings	-	+	+	+
Nutrient enrichment	N deposition	-	-	-	-
	Slurry application	-	-	+	=

The climate change variables included in Bunce et al. (2018) were revised using the UKCP18 Probabilistic Climate Projections, which are the primary tool for assessment of the ranges of uncertainties for five emission scenarios (Fung et al. 2018). Probabilistic anomalies in precipitation (mm/day) and mean temperature (^oC) for the future period 2020-2049, as compared to the 1980-2010 baseline, were obtained for the UK for two climate scenarios or Representative Concentration Pathways (RCP) (van Vuuren 2011). RCP2.6 and RCP8.5 were chosen to represent the best- and worst-case scenarios. The RCP2.6 simulates an average increase in global mean surface temperature of 1.6^{o}C while the RCP8.5 simulates mean increase of 4.3^{o}C over 2081-2100 compared to the pre-industrial period. The obtained cumulative probability density functions were discretised into three intervals or risk-classes representing a likely ‘increase’, ‘no-change’ and ‘decrease’ in precipitation and temperature, and the probability of each risk class for the summer and winter seasons, respectively, was calculated. It is apparent that over the next 30 years (2020-2049), the differences in projected temperature and precipitation anomalies between the two emission scenarios are quite modest.

Table 2.2: Overview of climate change variables included in the BBN and the probability of change under two different emission scenarios RCP2.6 and RCP8.5 over the 2020-2049 period.

Other stressors		**Low emission RCP2.6**		**High emission RCP8.5**	
		Winter %	**Summer %**	**Winter %**	**Summer %**
Mean seasonal temperature change ^oC	Increase (+1 to +2.5)	33	61	46	62
	No change (0 to +1)	57	36	48	35.5
	Decrease (-0.5 to 0)	10	3	6	2.5
Mean seasonal precipitation change %	Increase (+5 to +20)	34	9	43	8
	No change (-5 to 5)	58	36	50	33
	Decrease (-26 to -5)	8	55	7	59
Specific humidity change	Increase (8 to 16)	28	24	35	27
	No change (0 to 8)	58	65	53	60
	Decrease (-6 to 0)	14	11	12	13

In the BBN model, the relationship between the management interventions and the economic scenarios needs to be specified as conditional probability tables (CPTs). Table 2.3 shows how the scenario-dependent trends presented in Table 2.1 are translated into conditional probabilities and incorporated in the BBN model. For simplicity and consistency, it is assumed that all changes in management interventions are modelled using the same set of probabilities (e.g., a ‘+’ for a given management intervention in Table 2.1 is always modelled as a 90%/7.5%/2.5% chance of increase/no change/decrease). The relationships between the interventions and the economic scenarios are uncertain, and as shown in Table 2.3, it is assumed that there is a 10% chance that the trends given in Table 2.1 are wrong (e.g. a ‘-’ is assumed to correspond to 90% chance of ‘decrease’, 7.5% chance of ‘no change’ and 2.5% chance of ‘increase’).

Table 2.3: Overview of how the scenario-dependent 'trends' in Table 2.1 are incorporated as conditional probabilities in the BBN.

Intervention	increase	no change	decrease
+	90%	7.5%	2.5%
=	5%	90%	5%
-	2.5%	7.5%	90%
?	33.3%	33.3%	33.3%

Habitats

The UK Biodiversity Action Plan (UKBAP) broad habitats were used to classify habitats/land uses in the logic maps and the same habitat classes have therefore been included in the BBN. Table 2.4 presents an overview of the habitats and how they are expected to be influenced by changes in different management interventions and climate variables. The management interventions and climate variables can affect the condition (C) (as understood by the UK BAP) and/or the extent (E) of a given habitat and the impact can be either positive (+), strongly positive (++), negative (-) or strongly negative (--). The links and trends shown in the table are largely based on the work by Bunce et al. (2018) and the logic maps (Reed et al., 2020) but have been further informed with information from the Managing Ecosystem Services Evidence Review (MESER) (Stone 2013) as well as on expert assessment at two interactive workshops.

In the original logic maps, the state of some habitats was dependent on a large number of management variables (e.g., dwarf shrub heath had more than 10 input variables). When developing BBNs, it is undesirable to have variables with too many parent nodes, as this creates very large CPTs which can quickly become too large for efficient computation or elicitation. To help alleviate this issue, a number of intermediate nodes have been introduced in the network (marked with blue shading in Table 2.4). These include:

- *Grazing pressure*: This node combines the impact from "sheep grazing", "cattle grazing" and "deer grazing" and also includes a "season" node to reflect that grazing impact can change seasonally depending on the considered scenario. Combining the impact from grazing was deemed appropriate, as the impact of grazing sheep, cattle and deer on a given habitat was expected to be similar (in terms of trend/direction). Only those habitats that were influenced by all 3 types of grazing in the original logic map have the combined grazing pressure nodes as a parent. Habitats that are influenced by less than 3 types of grazing are directly linked to those grazing types.
- *Urbanisation pressure*: This node combines the impact from the urbanisation nodes, as defined by Bunce et al. (2018), i.e., "recreation", "mass events" and "new buildings". Combining the impact from these 3 nodes was again deemed appropriate as the impact from each of these on a given habitat was expected to be similar and all 3 tend to influence the same habitats.
- *Nutrient enrichment*: This node combines the impact from 'N deposition' and 'slurry application'. Again, these two nodes tend to impact the same habitats and their individual impact on given habitats are expected to be similar (cf. Table 2.4).

Table 2.4. Overview of the habitats included in the BBN and how they are expected to change based on changes in the different management interventions and climatic variables. Management interventions and climate variables can affect the condition (C) and/or extent (E) of a given habitat and the impact can be either positive (+), strongly positive (++), negative (-) or strongly negative (--). Interventions marked in blue combine related interventions to reduce model complexity (see explanation in 2.2.3 above).

Management and	Increase (+)/ decrease (-)	Broadleaved woodland	Conifer woodland	Boundary & linear	Arable	Improved grassland	Seminatural grassland	Bracken	Dwarf shrub heath	Fen, marsh, swamp	Bog	Montane habitats	Inland rock	Open water & canal	Rivers & streams
Sheep grazing intensity	+	C--		C-		C-	C-		C-	C-	C-	C-	C--		
	-	C++		C+		C+	C+		C+	C+	C+	C+	C++		
Cattle grazing intensity	+	C-				C-	C-	E--	C-	C-	C-				
	-	C+				C+	C+	E++	C+	C+	C+				
Deer grazing intensity	+	C-							C-		C-				
	-	C+							C+		C+				
Grazing intensity	+	C-				C-	C-		C--	C-	C-			C-	C-
	-	C+				C+	C+		C+	C+	C+			C+	C+
Pesticides/herbicides	+				C+	C+	C--							C-	C-
	-				C-	C-	C++							C+	C+
Artificial fertiliser	+				C+	C+	C*--			C-				C-	C-
	-				C-	C-	C+			C+				C+	C+
Silage	+					E++	E--								
	-					C--	E++								
Hay	+						CE++								
	-						CE--								
Drainage	+					C+				E--				C--	C--
	-					C-				C++				C++	C++
Managed burning	+						C-		C-		C-				
	-						C+		C+		C+				
Grouse - tracks	+								CE--		CE--				
	-								CE++		CE++				

Management and	Increase (+)/ decrease (-)	Broadleaved woodland	Conifer woodland	Boundary & linear	Arable	Improved grassland	Seminatural grassland	Bracken	Dwarf shrub heath	Fen, marsh, swamp	Bog	Montane habitats	Inland rock	Open water & canal	Rivers & streams
Planting of broadleaf	+	E++	E--			E-	E-	E-							
	-	E--	E++			E+	E+	E+							
Planting of conifer	+	E--	E++			E-	E-	E-			E-				
	-	E++	E--			E+	E+	E+			E+				
Landscape protection	+	C++		CE+			CE++		CE++	CE++	CE++	CE++	CE++		
	-	CE--		CE-			CE--		CE--	CE--	CE--	CE--	CE--		
Bog restoration	+		E--								E++				
	-		E++								E--				
Bog re-wetting	+										C++				
	-										C--				
Enhancing boundary & linear	+			CE++	E-	E-									
	-			CE--	E+	E+									
Mass events	+						C-		C-	C-	C-	C-	C-	C-	
	-						C+		C+	C+	C+	C+	C+	C+	
Recreation	+						C-		C-		C-	C-	C-		
	-						C+		C+		C+	C+	C+		
Urbanisation pressure	+						C-		C-	C-	C-	C-	C-	C-	
	-						C+		C+	C+	C+	C+	C+	C+	
N deposition	+								C-	C-	C-			C-	C-
	-								C+	C+	C+			C+	C+
Slurry application	+					C+	C--		C-	C-	C-			C--	C-
	-					C-	C++		C+	C+	C+			C++	C+
Nutrient enrichment	+								C-	C-	C-			C*-	C-
	-								C+	C+	C+			C*+	C+

Management and	Increase (+)/ decrease (-)	Broadleaved woodland	Conifer woodland	Boundary & linear	Arable	Improved grassland	Seminatural grassland	Bracken	Dwarf shrub heath	Fen, marsh, swamp	Bog	Montane habitats	Inland rock	Open water & canal	Rivers & streams
Mean seasonal temperature change	**+**				C-		C-		C--		C--	E--	C-		C-
Mean seasonal precipitation change	**+**								C++	C++	C++				CE+
	-								C--	C--	C--				CE-
	-								C--	C--	C--				CE-

In the BBN model, the relationships between the management interventions and the habitats again have to be specified as CPTs. Because the habitats in many cases are influenced by multiple management intervention and/or climate variables (cf. Table 2.4), the resulting CPTs are often rather large, which makes the elicitation of probabilities challenging. For example, seminatural grassland condition has 9 parent nodes each with 3 state values (increase/no chance/decrease), resulting in 3^9= 19,683 possible combinations of parent states for which the conditional probability of grassland condition must be specified. Unless a very large dataset or some model is available, it is not feasible to elicit probabilities for a CPT with this many combinations manually based on literature reviews or expert opinion. It was therefore decided to use so-called Noisy-Adder models (Zagorecki, 2010) when eliciting the CPTs for the habitat nodes. Noisy-Adders are canonical probabilistic models which derive the probability of the effect on a child node by taking the average of probabilities of the effect given each of the causes (i.e., the parent nodes) in separation. Because of this, the number of probability elicitations can be dramatically reduced, especially when the number of parents of a node becomes large. In the example for seminatural grassland, the number of probability elicitations reduces to 9*(3-1) + 1 = 19.

To apply Noisy-Adder models, distinguished states of the parent nodes first have to be defined. The distinguished states of the parent nodes do not have any influence on the child node. For the BBN modelling here, it is always assumed that the distinguished state is the 'no change' state. The next step is to specify the net probabilities of the child node given the various states of each of its parents, assuming that the other parents are all in their distinguished states. Table 2.5 shows an overview of how the 'trends' presented in Table 2.4 have been translated into net probabilities for the Noisy-Adder models in the BBN. For simplicity and consistency, it is assumed that the same set of net probabilities can be used for modelling the changes in all habitat types (e.g., a strongly positive impact on the condition of a given habitat ('C++') in Table 2.4 is always modelled using a 95%/5%/0% net probability of increase/no change/decrease in habitat condition, regardless of the type of habitat and type of intervention).

The relationships between the interventions and habitats are uncertain. This has partly been reflected through the net probabilities in Table 2.5 by assuming that e.g., a positive impact (+) on a given habitat only corresponds to 85% chance of 'increase', and 10% and 5% chance of 'no change' and 'decrease', respectively. However, Noisy-Adder models also include a so-called leak distribution, which describes the influence of all unmodeled causes and basically represents the uncertainty when all parents are in their distinguished state. As shown in Table 2.5, we are here using a leak distribution which assumes that there is a 10% chance of a change in habitat condition/extent when all other causes are in their distinguished state.

Table 2.5: Overview of how the relationships between management and habitats in Table 2.4 are translated to net probabilities and used for populating the CPTs in the BBN.

Habitat change	**increase**	**no change**	**decrease**
++	95%	5%	0%
+	85%	10%	5%
-	5%	10%	85%
--	0%	5%	95%
Leak	5%	90%	5%

Finally, when applying Noisy-Adder models it is possible to assign weights to each of the parent nodes as well as to the leak distribution, and the resulting CPT is then calculated through weighted averaging. For the work here, it is generally assumed that the weight of all parent nodes is $w_p = 1$, whereas the weight of the leak factor is set to 0.1. However, parent nodes that are an amalgamation of multiple intervention nodes (e.g., grazing pressure) are assigned a weight that reflect the number of nodes included in the amalgamation. Examining the robustness of these weights, the impact of changes and sources of data for parameterisation is a priority area for further model development.

Ecosystem services

An overview of the ecosystem services included in the BBN is presented in Table 2.6. Table 2.7 shows how the ecosystem services are expected to change in relation to changes in habitats. For the development of the original logic maps (Reed et al., 2020), ecosystem service links were taken from Lusardi et al. (2018), which contains logic chains used to identify the Natural Capital Indicators that affect for provisioning, regulating and cultural services for the habitats. Links were derived via expert analysis from the UK National Ecosystem Assessment (2011) and its official follow-on document (UK National Ecosystem Assessment 2014) and classified using the Common International Classification of Ecosystem Services (CICES) version 4.3 (Haines-Young & Potschin 2013) (note version 5.1 is now available: https://cices.eu/). From a total of 51 logic chains, only those produced for habitat categories of relevance to typical upland landscapes were selected, namely Woodland; Catchment; Freshwaters: open waters, wetlands, & floodplains; Mountain, moorland & heath; Enclosed farmland; and Semi-natural grassland. These relationships from the logic map were represented in the model.

Because some of the ecosystem services depends on the state of a large number of habitats, it was decided to introduce intermediate nodes that combine habitat extent and habitat condition (Table 2.7). For combined nodes (e.g.woodland overall), where the effects differ, these are split as 50% - 50% for each trend relevant to the contributing habitats.

Table 2.6. Overview of ecosystem services included in the BBN. Ecosystem service flow indicators and benefits based on Lusardi et al. (2018).

Ecosystem service	Ecosystem service flow indicators	Benefits
Biomass (woodland)	Production of timber, paper & other wood products + Wood-based fuel harvested (for plant-based energy)	Timber, paper and other products from wood + energy from wood
Biomass (animals)	Number of reared animals	Products from animals e.g., meat, dairy products, honey
Biomass (crops)	Production of crops	Food from crops e.g., cereals, vegetables, fruit
Climate regulation	Carbon sequestered & greenhouse gases fixed; local urban cooling	Equitable climate e.g., reduced risk of drought, flood & extreme weather events, lower summer temperatures, reduced health & safety risks, reduced flood risk, protection of infrastructure/lack of transport disruption
Maintaining of habitats and nursery populations	Maintenance of sustainable ecosystems & life cycle stages	Biodiversity, in of itself, and underpinning all other services such as recreation (incl. wildlife watching), tourism, research and education, food from wild populations &

		aquaculture, flood protection (sea grass beds, dunes), climate regulation
Water filtering	Water quality (chemical and biological, incl. viral & bacterial)	Clean water, also underpinning e.g., water supply, sustainable ecosystems, cultural services, human health benefits.
Flood mitigation (Flood protection)	Regulation of flow regime for peak events	Reduced flood risk, affecting e.g., reduced health & safety risk, protection of housing, businesses & infrastructure, lack of transport disruption
Mass stabilisation & erosion control	Stabilisation of soil/sediment	Erosion control e.g., soil/land retention, lack of transport disruption, protection of housing, businesses & infrastructure, reduced health & safety risk, reduced flood risk
Fire reduction potential (CICES 5.1)	The capacity of ecosystems to reduce the frequency, spread or magnitudes of fires. (e.g.wetland area between forests, or fire belt in woodland containing species of low combustibility)	Reduction in fire damage costs. However, in the current version of the model this ES is not included in the economic valuation due to lack of available data. Instead, it is positively linked to 'Climate regulation ES', which is included in the economic valuation.
Pest & disease control	Abundance & species richness of pest controlling species; intact fungal networks to reduce infections in plants	Natural control of agricultural pest species and diseases
Pollination & seed dispersal	Abundance, distribution & species richness of pollinators & seed dispersers	Pollination underpinning cultivated crops dependent on insect pollination e.g., field beans, apples, plums, pears, cucumbers, plums, strawberries, oil seed rape
Cultural services	Based on proximity and accessibility of green space and blue space in relation to people and represented by the interactions people have with the natural environment (practices): -Experiential and physical use: Number of visits, duration of visits, range of activities undertaken and the number of people carrying out each activity, frequency and time spent. - Scientific and educational use: Number of research projects, PhD/Masters projects, number of school visits.	Generic aspects of wellbeing that can be associated with the interactions between people and the natural environment: Identities (e.g.belonging; sense of place; rootedness; spirituality; sense of history); Experiences (e.g. tranquillity; inspiration; escape; discovery); Capabilities (e.g. knowledge; health; dexterity; judgement); Non-use values: existence, bequest, altruistic; option)

Table 2.7: Relationship between habitats and ecosystem services. The relationships marked in light grey were excluded from the final model to reduce computational complexity – these will be included in future model development.

HABITAT		**Biomass - woodland**	**Climate regulation**	**Maintaining nursery**	**Flood mitigation**	**Water filtering**	**Mass stabilisation & control of**	**Biomass - animals**	**Biomass - crops**	**Pest & disease control**	**Pollination & seed dispersal**	**Cultural services**
Broadleaved woodland	**+**	+	+	+	+	+	+					+
	-	-	-	-	-	-	-					-
Conifer woodland	**+**	+	?	+	?	?	?					?
	-	-	-	+	?	?	?					+
Boundary & linear	**+**	+		+	+	+	+			+	+	+
	-	-		-	-	-	-			-	-	-
Arable	**+**		-			-			+			
	-		+			+			-			
Improved grassland	**+**		-			-		+				
	-		+			+		-				
Seminatural grassland	**+**		+	+	+	+	+	-			+	+
	-		-	-	-	-	-	+			-	-
Bracken	**+**											
	-											
Dwarf shrub heath	**+**		+	+	+	+	+	-			+	+
	-		-	-	-	-	-	+			-	-
Fen/marsh/swamp	**+**		+	+	+	+						+
	-		-	-	-	-						-
Bog	**+**		+	+	=	+	+					+
	-		-	-	-	-	-					-
Montane habitats	**+**			+							+	+
	-			-							-	-
Inland rock	**+**			+								+
	-			-								-
Open water & canal	**+**			+								+
	-			-								-
Rivers and streams	**+**			+								+
	-			-								-
Fire reduction potential	**+**		+									
	-		-									

Table 2.8: Overview of how the relationships between habitats and ecosystem services in Table 2.4 are translated to net probabilities and used for populating the CPTs in the BBN.

Habitat change	**Ecosystem Service**		
	Increase	**no change**	**decrease**
+	95%	5%	0%
-	0%	5%	95%
?	33%	33%	33%
Leak	5%	90%	5%

Ecosystem services qualitative assessment

The ecosystem service qualitative assessment is based on available evidence on the economic values associated to ecosystem services in upland areas or at the UK or England aggregated levels. UK natural capital account estimates (ONS, 2020a), UK woodlands natural capital accounts (ONS,2020b), the statistical bulleting of UK natural capital in peatlands (ONS, 2019), Forestry Statistics (Forest Research 2020), and the Greenhouse Gas (GHG) emissions inventory (BEIS, 2020) were used to provide evidence on the relative importance of ecosystem services such as biomass from woodlands for timber and energy (biomass), outdoors recreation (i.e., considering mainly mountain, moor, and hill areas), carbon sequestration and GHG emissions, and biomass and income from agriculture (crops and livestock).

Economic valuation studies for other ecosystem services such as water filtering, flood mitigation, erosion control, pest and disease control, pollination, cultural services and maintenance of habitats and nursery populations for wild animals and plants provide fragmentary and incomplete picture of the economic value that those ecosystem services have for society. These studies (mainly peer-reviewed scientific publications) use various economic valuation methods from market and cost-based valuation to revealed and/ or stated preference approaches. Those economic results cannot be consistently aggregated or directly used to estimate the socio-economic effect of contrasting future policy scenarios without significant evidence synthesis input, which may simply highlight uncertainty surrounding combination of different metrics from different contexts.

Rather a qualitative assessment approach is used to judge the relative importance of those ecosystem services in two ways. First, in terms of ecosystem services contribution to private and public benefits uplands deliver. Second, in terms of the importance that uplands in UK have for the provision of the set of ecosystem services considered in this report. The qualitative assessment contemplates scores from 1 to 5, where 1 represent very low importance and 5 very high importance. In addition, the uncertainty level involved in the estimation of the economic values for the ecosystem considered is also provided using scores on the scale of 1.1 to 1.5 to represent the very low to very high uncertainty level (see

Table 2.9)

Table 2.9. Qualitative assessment of the importance of ecosystem services and uncertainly involved in their economic valuation. Importance has received scores on the 1-5 scale while uncertainty was scored on a 1.1-1.5 scale to represent Very Low to Very High ranks

Ecosystem services	Importance (in terms of the benefits produced in the uplands)	Importance (of the uplands in the provision of ecosystem services)	Uncertainty level (in the estimation of economic values)
Biomass woodland: fuel	Low	Very low	Low
Biomass woodland: timber	High	Low	Low
Climate regulation: woodland and grassland	High	Low	Medium
Climate regulation: sequestration and GHG emissions from peatland	High	Low	Medium
Climate regulation: GHG emissions from crop and livestock production	Medium	Medium	Medium
Biodiversity - charismatic species	Unclear	Unclear	Very high
Water filtering: drinking water	Low	Low	High
Water filtering: Environmental water	Low	Low	High
Flood protection	Medium	Medium	Medium
Biomass from livestock farming	Very high	High	Low
Pest and disease control	Unclear	Unclear	Very high
Pollination	Low	Low	Very high
Cultural services: recreation	Medium	Medium	High
Cultural services: shooting and fishing	Medium	Very high	High
Cultural services: tourism	Medium	Medium	High

Legend: Very high, High, Medium, Low, Very low, Unclear

In the model, the scores of the two Importance categories for each ecosystem service were multiplied to estimate a mean of a normal distribution, while the scores for uncertainty were used to represent a standard deviation of this distribution. Minimum, mean and maximum values from these normal distributions of estimated values were then used in the model to represent the ecosystem services utility values.

The following ecosystem services were either not included or not valued in the model:

- Wellbeing, although requested at the stakeholder workshop, was not included among the evaluation of Ecosystem Services as this is deemed to be an Ecosystem Benefit and is implicitly included in the economic valuation of other Ecosystem Services.
- Similarly, infrastructure green and grey, although requested at the stakeholder workshop, was not included in the model. Green infrastructure is a “network of natural and seminatural areas with other environmental features (e.g.boundary and lineal features) designed to deliver a wide range of ecosystem services” (EC 2013). Grey infrastructure usually refers to human engineered structures (e.g., reservoirs), and along with ecosystem components contributes to create ecosystem benefits. The economic valuation of the ecosystem benefits delivered by these infrastructures would be too complex and beyond the scope of the current model.
- Furthermore, we cannot offer credible qualitative scores of the importance of ecosystem services to deliver economic benefits in the uplands for both biodiversity and pest and disease control and therefore these ecosystem services were not evaluated in the model in economic terms. We couldn’t find robust evidence of the benefits of pest and disease control in upland habitats, and the few available studies focus on forest disease control but not specifically connected to the ecosystems’ capacity for regulating pests and diseases. Biodiversity refers to the diversity of life, from the diversity of genes, species to the diversity of ecosystems, and we still have limited understanding of it’s underpinning of other ecosystem services. Therefore, biodiversity valuation studies based on charismatic species or habitats provide a

fragmentary and narrow representation of the importance of biodiversity for enabling ecosystem productivity, resilience and underpinning benefits to humans. Biodiversity, indeed, underpins all other Ecosystem Services, contributing to economic activities and human livelihoods and wellbeing in complex and interrelated ways, and henceforth its value surpasses the valuation of all other benefits (Dasgupta 2021), possibly by many orders of magnitude. The exclusion of these values for biodiversity from the model should therefore not be taken to suggest that they are un-valuable, rather that they are beyond our ability to value.

Wildfire sub-model

The conceptual model for the wildfire sub-model (Figure 2.2) was constructed using expert opinion from within the research team (Dr Gareth Clay, University of Manchester and Dr Zisis Gagkas, The James Hutton Institute). The model was parameterised using this expert opinion as well as literature (Glaves et al., 2020). Terminology was informed by Jesús San-Miguel-Ayanz, *et al*. (2018).

Fire behaviour and spread are primarily determined by three key factors: meteorology, topography and fuels. As this is a non-spatially explicit approach, topography could not be considered in the sub-model. Fire danger rating systems (FDRS) are one way of anticipating the ignition probability, spread and potential damage from wildfires. These systems are often based on empirical models where the key inputs are meteorological variables and fuel condition (Planas and Pastor, 2013). Although this sub-model is not an operational model or predictive on the timescales normally used with FDRSs (e.g. daily, seasonally), the importance of meteorology and fuel is reflected in this sub-model.

It should be also noted that this does not include mechanistic linkages between nodes (e.g. climate variables and fuel moisture). At present, we do not yet have sufficient information for many of these relationships for UK fuels and climates, though ongoing research projects will develop this in time (i.e. Scottish FDRS project[1] and UK FDRS project[2]). As noted elsewhere in the report, this could be developed in future iterations of the sub-model and BBN.

Figure 2.2 below shows the variables related to climate change and those that are specific to the Wildfire sub-model for simplicity. Figure 2.7. also shows additional linked variables from the wider Uplandia model for a comprehensive overview. The variables from the wider Uplandia model connected to ‘Fuel amount related to condition’ and ‘Fuel type amount related to habitat extent’ were weighted according to their relative extent in upland landscapes (Bunce et al. 2018b). Thus, woodland and bog received a weighting of ‘1’ while semi-natural grassland the shrub heath received a weighting of ‘2’. The contribution of ‘Intentional ignition’ to ‘Ignition source’ was weighted according to Glaves et al. (2020), whereby ‘Accidental ignition’ was responsible for 23%, Intentional ignition for 76% and Lightning for 1% of ignitions.

[1] https://www.scottishfiredangerratingsystem.co.uk/
[2] www.ukfdrs.com

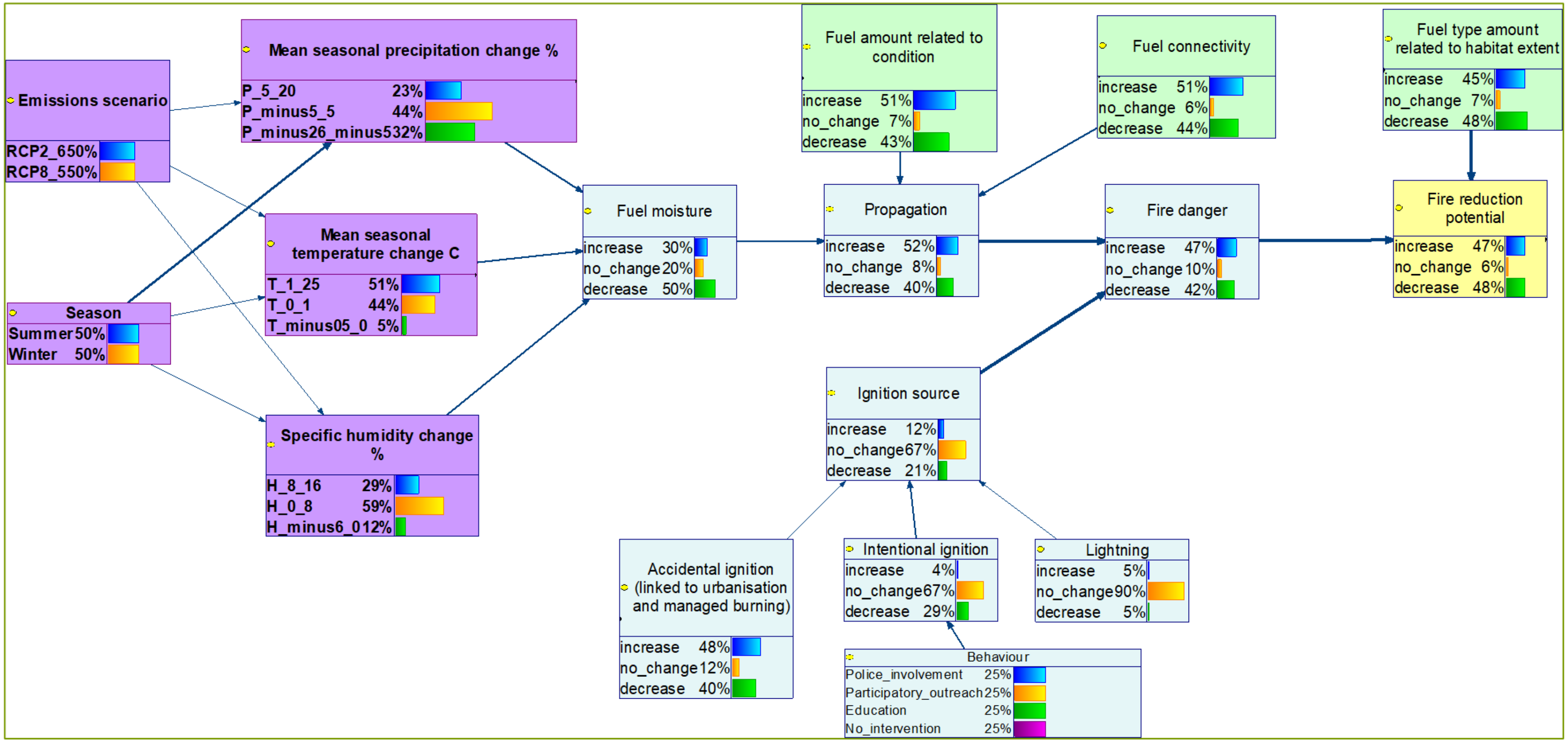

Figure 2.2. The conceptual wildfire sub-model structure. Thickness of arrows shows the strength of influence between vriables (thicker lines show a stronger correlation measured in Euclydean distance).

Table 2.10. Relationships between wildfire risk factors and fire risk.

CHILD NODE			PARENT NODES			
Model node	**Definition**	**States**	**Parent node 1**	**Parent node 2**	**Parent node 3**	**Parent node 4**
Emissions scenario	Low and high emissions scenarios from UKCP 2018	RCP 2.6 RCP 8.5	50% 50%			
Season		Summer Winter	50% 50%			
Mean seasonal precipitation change %	Precipitation anomaly on 1980-2010 baseline for 2020-2049 period from UKCP 2018.	5_20 minus5-5 minus 26-minus5	**Season:** Probabilities calculated from CC predictions	**Emissions scenario:** Probabilities calculated from CC predictions		
Mean seasonal temperature change C	Temperature anomaly on 1980-2010 baseline for 2020-2049 period from UKCP 2018.	1_25 0-1 minus 0.5-0	**Season:** Probabilities calculated from CC predictions	**Emissions scenario:** Probabilities calculated from CC predictions		
Specific humidity change %	Specific humidity anomaly on 1980-2010 baseline for 2020-2049 period from UKCP 2018.	_8-16 0-8 minus 6-0	**Season:** Probabilities calculated from CC predictions	**Emissions scenario:** Probabilities calculated from CC predictions		
Fuel moisture	Links to Propagation	increase no change decrease	**Mean seasonal precipitation change %:** Strong proportional relationship	**Mean seasonal temperature change %:** Strong inversely proportional relationship	**Specific humidity change %:** Strong proportional relationship	

Propagation	Links to Fire Danger	increase no change decrease	**Fuel moisture:** Strong inversely proportional relationship	**Fuel amount related to condition:** Strong proportional relationship	**Fuel connectivity**: Strong inversely proportional relationship	
Fuel type amount related to habitat condition	Links to Propagation	increase no change decrease	**Blanket bog condition:** Strong inversely proportional relationship	**Seminatural grassland condition:** Strong inversely proportional relationship	**Woodland condition:** Strong inversely proportional relationship	**Shrub heath condition:** Strong inversely proportional relationship
Fuel connectivity	Conditioned on managed burning and grazing.	increase no change decrease	**Managed burning**: Strong inversely proportional relationship	**Grazing**: Strong inversely proportional relationship		
Fire danger	Links to Fire Reduction Potential	increase no change decrease	**Propagation**: Strong proportional relationship	**Ignition source**: Strong proportional relationship		
Fuel type related to habitat extent	Links to Fire Reduction Potential to represent severity	increase no change decrease	**Blanket bog extent:** Strong proportional relationship	**Seminatural grassland extent:** Strong proportional relationship	**Woodland extent:** Strong proportional relationship	**Shrub heath extent:** Strong proportional relationship
Ignition source	Links to Fire Danger	increase no change decrease	**Lightning frequency:** Strong proportional relationship	**Intentional ignition frequency:** Strong proportional relationship	**Accidental ignition frequency:** Strong proportional relationship	

<table>
<tr><td>Lightning frequency</td><td>Links to Ignition source</td><td>increase
no change
decrease</td><td>5%
90%
5%</td><td></td><td></td><td></td></tr>
<tr><td>Intentional ignition frequency</td><td>Conditioned on Behaviour, links to Ignition source</td><td>increase
no change
decrease</td><td colspan="4">Behaviour: probabilities informed by literature review (Jollands 2011)
<table>
<tr><th></th><th>Police involvement</th><th>Participatory outreach</th><th>Education</th><th>No intervention</th></tr>
<tr><td>increase</td><td>0.05</td><td>0.05</td><td>0.05</td><td>0</td></tr>
<tr><td>no_change</td><td>0.35</td><td>0.49</td><td>0.85</td><td>1</td></tr>
<tr><td>decrease</td><td>0.6</td><td>0.46</td><td>0.1</td><td>0</td></tr>
</table></td></tr>
<tr><td>Accidental ignition frequency</td><td>Links to ignition source</td><td>increase
no change
decrease</td><td>Urbanisation: Proportional relationship</td><td>Managed burning: Proportional relationship</td><td></td><td></td></tr>
<tr><td rowspan="4">Behaviour</td><td rowspan="4">Linked to Intentional ignition frequency</td><td>Police involvement</td><td>25%</td><td rowspan="4"></td><td rowspan="4"></td><td rowspan="4"></td></tr>
<tr><td>Participatory outreach</td><td>25%</td></tr>
<tr><td>Education</td><td>25%</td></tr>
<tr><td>No intervention</td><td>25%</td></tr>
<tr><td>Fire reduction potential</td><td>Ecosystem service flowing from Fire risk</td><td>increase
no change
decrease</td><td></td><td></td><td></td><td></td></tr>
</table>

Table 2.11: An overview of probabilities assigned to the relationships in the wildfire sub-module summarised in Table 2.10 and used for populating the CPTs in the BBN.

Habitat change	increase	no change	decrease
Strong proportional relationship	95%	5%	0%
Proportional relationship	85%	10%	5%
Inverse proportional relationship	5%	10%	85%
Strong inverse proportional relationship	0%	5%	95%
Leak	5%	90%	5%

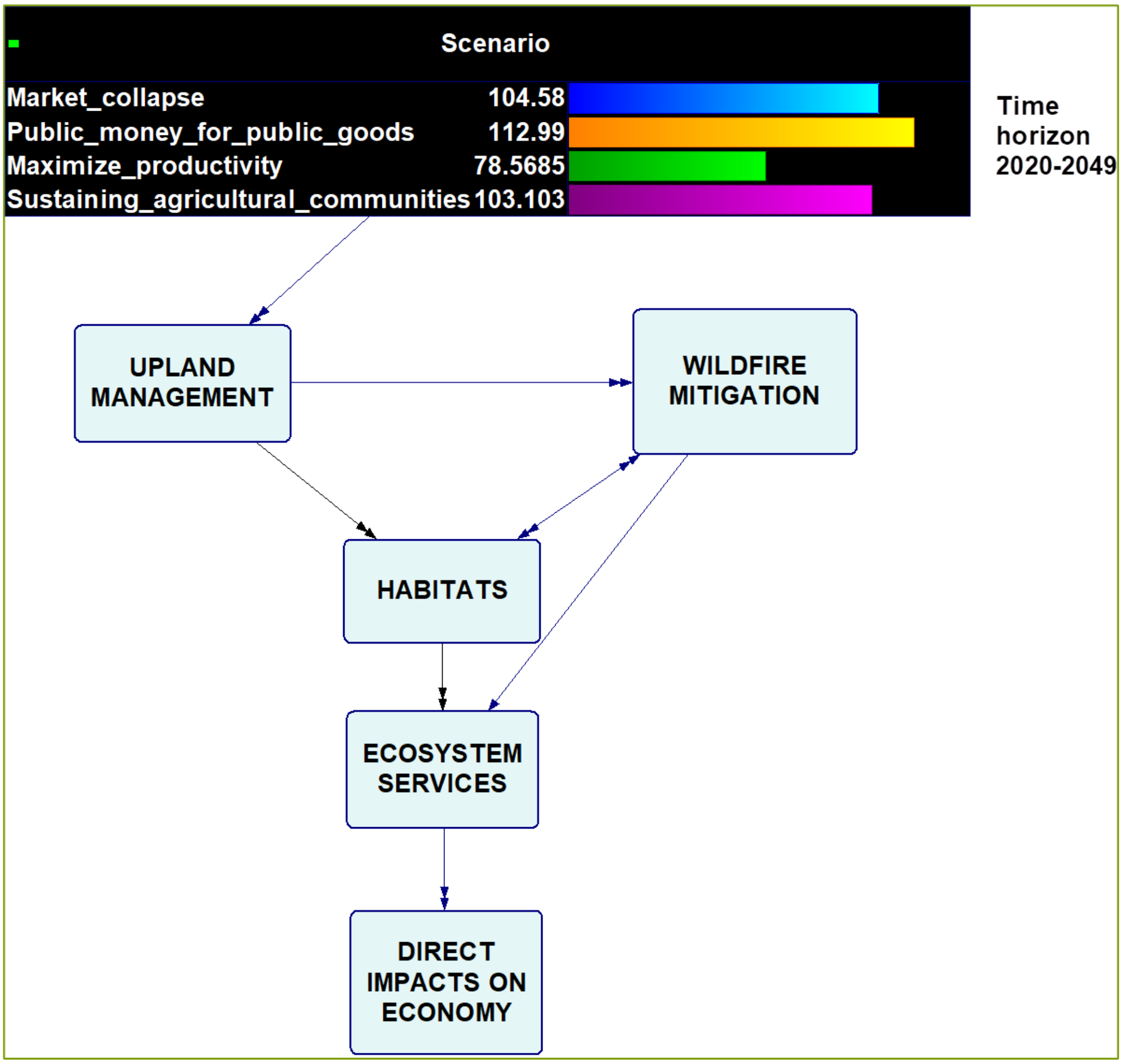

Figure 2.3. Overall utility values of the four simulated scenarios

2.3 Probabilistic inference and results

Figure 2.3. below shows the overall model structure, including sub-models. The scenario node shows the calculated overall utility of each scenario. It is apparent that the ‘Maximise productivity’ scenario results in the smallest utility of app. 78 on a notional ranked scale, while the ‘Public money for public goods’ scenario results in the largest overall utility of app. 113. This analysis suggests that the ‘Public money for public goods’ represents the most optimum policy option under these scenarios. However, in order to evaluate an optimum policy decision, the model would need to be extended to a full Influence Diagram, including expected costs and benefits (where robust monetary data is available) associated with change in the provision of ecosystem services due to changes in ecosystem extent and condition. Stated preferences methodologies or other forms of elicitation could be employed where data is unavailable or direct monetisation of ecosystem services is controversial. This represents another priority area for further development.

Figures 2.4-2.6 show the results of ‘forward inference’ for ecosystem services, the economic valuation in terms of ‘utility’ and for one particular ecosystem service ‘Fire reduction potential’ under the four policy scenarios.

Fig. 2.7 shows the results of ‘backward inference’ whereby hard evidence is set on the ‘Fire reduction potential’ to select a 100% probability of ‘increase’. The remaining nodes then show the marginal probability of the remaining variables in the model, given the ‘increase’ in ‘Fire reduction potential’ outcome. This is an example of how the model could be used to optimise decisions for a single outcome. However, for a full decision support analysis, several outcomes should be optimised simultaneously (multi-objective optimisation) and costs as well as benefits should be considered.

Fig. 2.8 shows an example of sensitivity analysis, with ‘Fire reduction potential’ set as target variable. The variables shown in red are the most sensitive, followed by those in paler colours until the least sensitivity variables shown in white. Sensitivity analysis helps to validate the model by investigating the effect of small changes in numerical parameters (i.e., probabilities) on the output parameters (e.g., posterior probabilities). Highly sensitive parameters affect the reasoning results more significantly. Sensitivity analysis is context-specific and depends on the choice of target variable – in this case the ‘Fire reduction potential’. The current model, implement in GeNIe software (bayesfusion.com), uses an algorithm proposed by Kjaerulff and van der Gaag (2000).

In addition, the thickness of arrows in Fig. 2.8 shows the strength of influence between variables, measured in Euclidean distance. Full evaluation of the strength of influence between all variables is reported in Appendix 1.

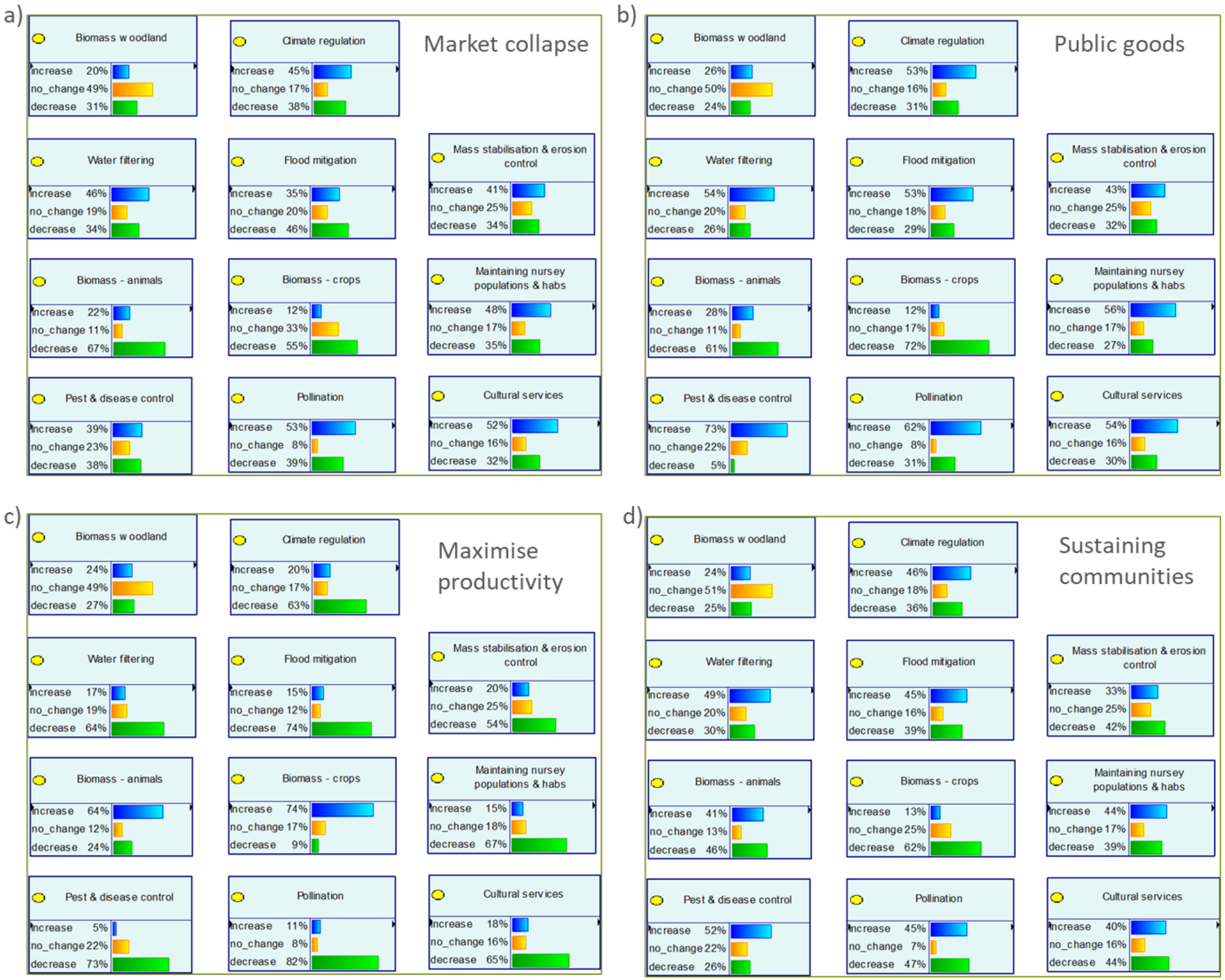

Figure 2.4. Ecosystem services change under four scenarios a) Market collapse b) Public money for public goods c) Maximise productivity d) Sustaining agricultural communities.

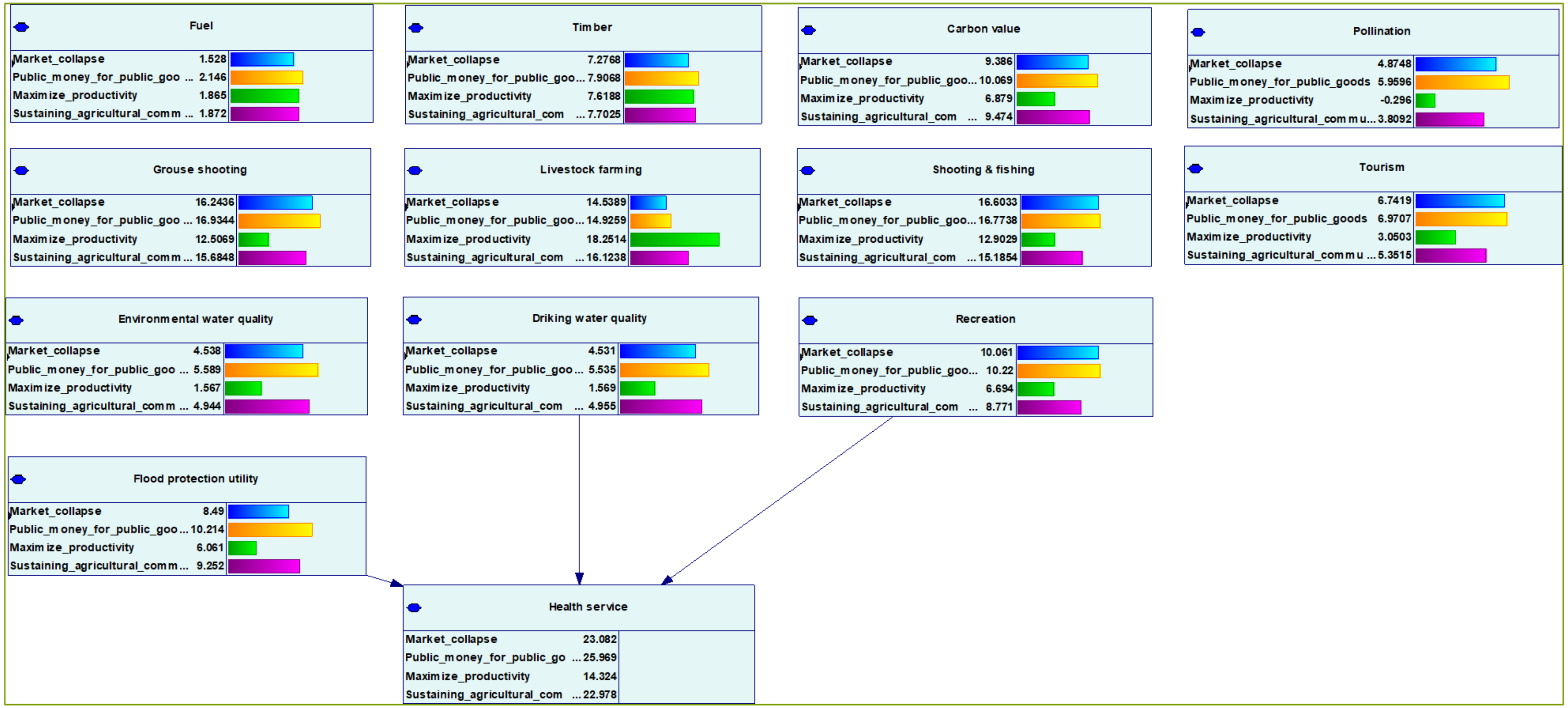

Figure 2.5. Ecosystem services Utility values under four policy scenarios

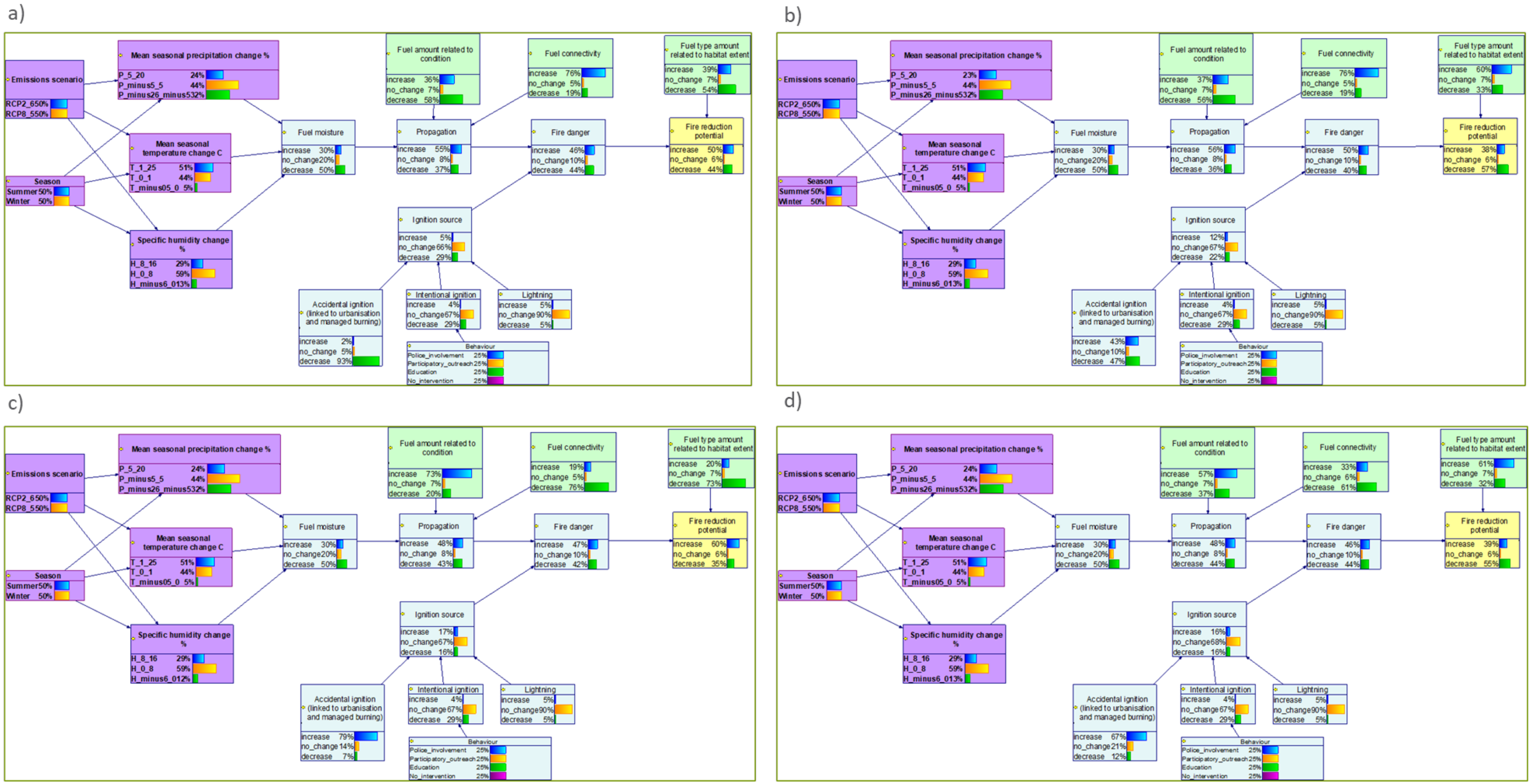

Figure 2.6. Wildfire sub-model Fire reduction potential risk simulations under four scenarios a) Market collapse b) Public money for public goods c) Maximise productivity d) Sustaining agricultural communities.

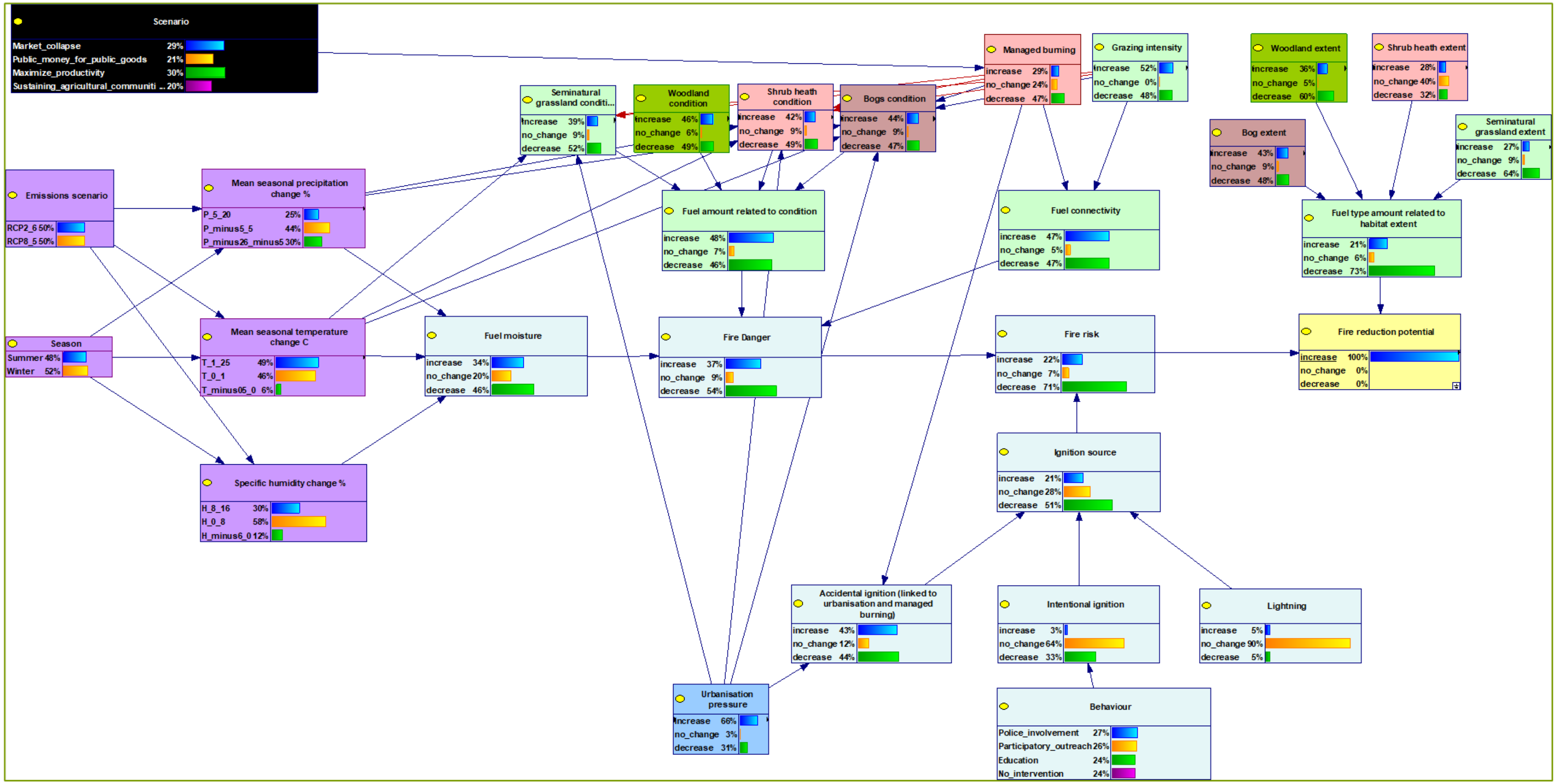

Figure 2.7. Backward inference – maximising Fire reduction potential

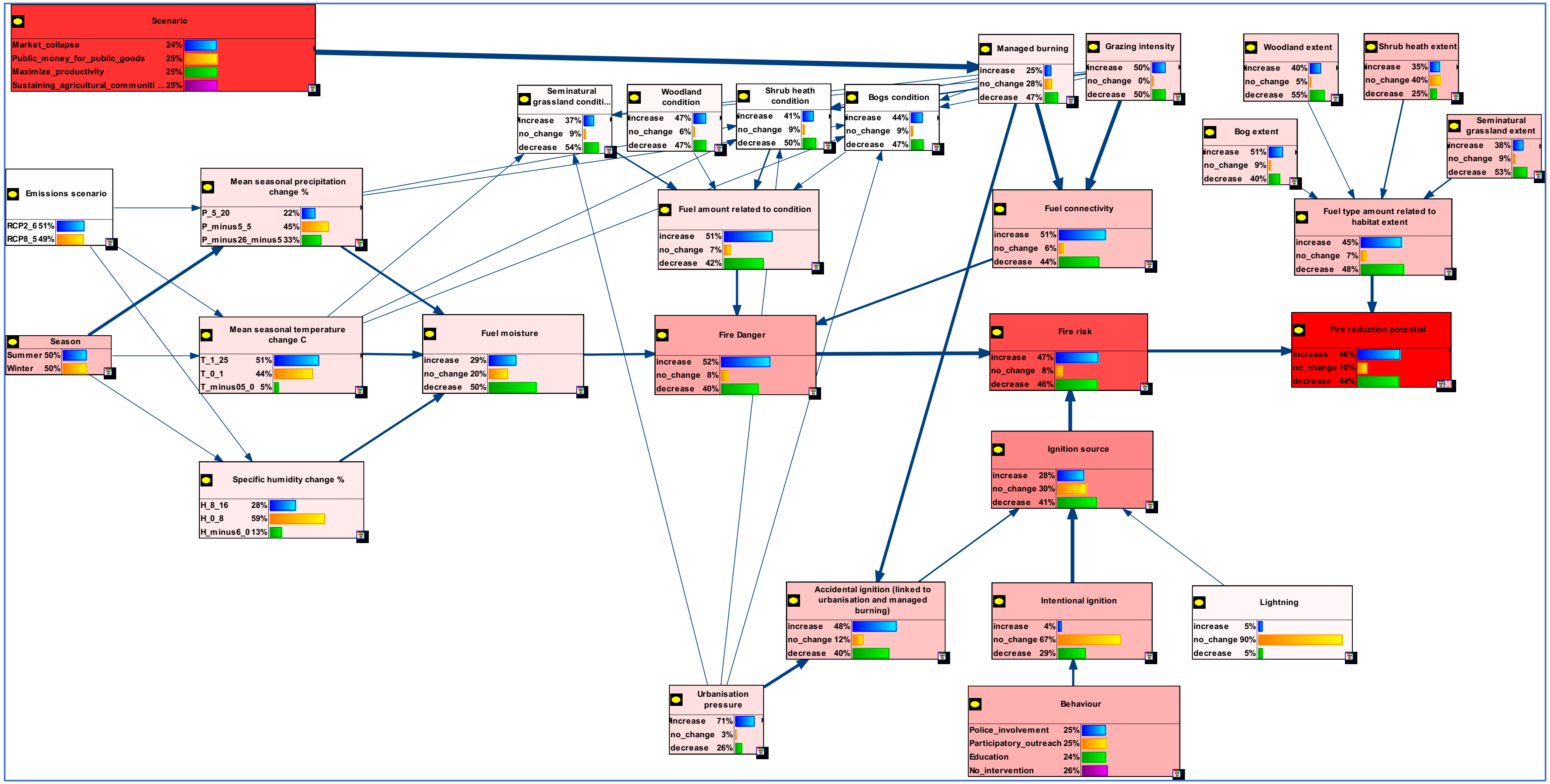

Figure 2.8. Wildfire sub-model sensitivity analysis, also showing links to all connected nodes from the larger Uplandia model.

2.4 Discussion, limitations and future directions

This project has developed a pilot model ('beta-version') to demonstrate the applicability of Bayesian Belief Networks as Decision Support Tool (DST) for the modelling of policy scenarios, ecosystem services and their economic utilities. The model, based on previous work by Reed et al. (2020), was further informed by experts and stakeholders at two virtual workshops. Currently, the model allows insights into the complexity of the system and demonstrates the potential functionality of this DST.

However, to achieve a full evaluation of optimal policy options, the following model improvements could be pursued:

- The evaluation of utilities should be extended to include costs, as well as benefits. This would allow full decision support and value of information analyses to inform policy decisions regarding interventions and data acquisition priorities.
- Many of the conditional relationships (CPTs) in the BBN are currently based on fairly generic assumptions regarding direction and strength of the relationship/trend. These CPTs could be further reviewed and refined with data and information from a wider literature review or elicitation exercises to obtain more nuanced relationships. Weighting of the interventions and drivers of change in extent and condition are important in this context.
- An interactive web-based interface could be developed to allow users to interrogate the model easily. This could be done either by linking the existing software platform Genie to a purpose-built web App using the Genie API or by implementing the model in the open-source R software e.g. the HydeNet package https://cran.r-project.org/web/packages/HydeNet/HydeNet.pdf. It is not possible to fully report the range of model predictions on paper because of systems complexity. An interactive tool would facilitate use as a decision support tool for any desired combination of interventions, habitats and ecosystem services.
- The model could be implemented spatially in GIS to allow place-specific spatial application, informing variables from available mapping datasets. This would help to refine the evaluation of trade-offs by considering local habitat extent and habitat trade-offs in a particular location. A spatial implementation of the model at a case study site with pre-existing data, e.g. the James Hutton Institute upland research farm at Glensaugh (1,000 ha) could also be tested.
- Further develop the Wildfire model as a hybrid dynamic BBN with both continuous and discrete variables to allow incorporation of feedbacks and incorporation of new data generated in ongoing research projects.

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3 Wildfire Rapid Evidence Assessment (REA)

Land manager and other upland user groups behaviours in relation to wildfire in the UK

3.1 Introduction

This report summarises the findings from a Rapid Evidence Assessment (REA) on the key factors that influence the behaviour of peatland users and managers, in relation to wildfire. These findings and the subsequent final REA report have been used to provide input to a Bayesian model that identifies key relationships, dependencies, feedbacks and uncertainties within the peatland social-ecological system that could mediate a range of potential policy outcomes. The resulting logic map integrates findings from this REA with evidence from across the wider upland system and data from existing computational models of upland systems or their component parts, where these exist. This provides a proof-of-concept method and a demonstration of the application of a probabilistic system modelling approach for the simulation of alternative policy scenarios.

Given the policy relevance and remaining uncertainty surrounding the role of wildfires in upland peat systems, the REA reviews the existing evidence base (and evidence gaps) relating to land management (and other user group) behaviour in relation to wildfire. Although the focus is on wildfire, both prescribed and wildfires play a significant role in the ecology of peatlands, and changes in the frequency, intensity and management of wildfires can impact significantly on biodiversity and ecosystem function, including carbon storage (Davies et al., 2008). As such, prescribed fire is considered as a potential mitigating or exacerbating factor in the REA. Wildfire risk depends on a combination of factors, including climate, land management (which can include prescribed burning as a management tool) and environmental change. Wildfires occur in different landcover contexts in the uplands, including traditionally managed moorland, forestry or native woodland settings and unmanaged peatlands. The REA takes this broader context into account in terms of the evidence selected for inclusion.

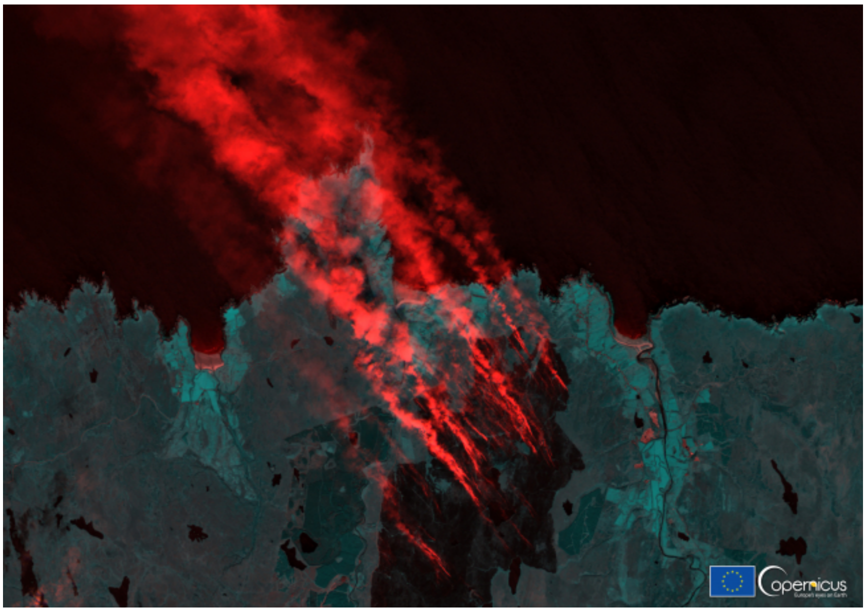

Image of a peatland wildfire in Sutherland from Space (Source: www.copernicus.eu)

Rapid Evidence Assessment

Rapid Evidence Assessment (REA) is one of a range of methods for reviewing and synthesizing large amounts of evidence related to a research question. REAs are similar to systematic reviews, but generally conducted on shorter timescales. REAs are particularly well suited to addressing policy-relevant questions, including the impacts of policy or management interventions. REAs follow a systematic approach and generally include a critical appraisal component to capture an unbiased and comprehensive sample of relevant evidence relating to the primary REA question. This REA broadly follows the Defra guidance for conducting REAs[3] and the PRISMA[4] (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach for designing and conducting a Rapid Evidence Assessment. The protocol developed for this review will be registered with the Open Science Framework[5], to ensure transparency and clarity around the process for how the evidence review was conducted.

This evidence assessment was conducted by researchers at Scotland's Rural College (SRUC) in collaboration with the University of Newcastle, from December 2020 to end of April 2021. This included four weeks to develop the protocol, eight weeks to review and critically appraise the collated evidence and a further four weeks to complete the review report. The review was conducted by three researchers following a transparent screening and selection process (see Section 3.3).

This report presents the REA process and protocol and key findings, including the REA search questions, the scope of the review and search strategy, search sources and search keywords, the process used for refining the search and critically appraising the evidence and an initial summary synthesis of results.

Policy Context

The research is designed to feed into policy development and implementation in England through the ongoing work of the Department for the Environment, Food and Rural Affairs (Defra) and Natural England. Uplands are a key priority for Defra and Natural England, given their importance for climate change mitigation, biodiversity, drinking water provision, flood risk mitigation, agriculture, recreation and culture. Uplands feature prominently in Defra's 25 year plan and peatlands (many of which are in the English uplands) are being targeted for restoration in the Nature for Climate Fund and forthcoming England Peat Strategy (to be delivered by Natural England), as part of the UK's plans to reach net zero emissions for the land use sector. Linked to this, legislation is now being brought forward to prevent the burning of heather and other vegetation on protected blanket bog habitats. However, little is known about how the cessation of burning (and possible replacement with mechanical cutting) might influence wildfire risk, especially in sites that are not in favourable condition, if these changes in management are not accompanied by restoration measures. More broadly, wildfire prevention has been a longstanding focus of work by Natural England in the uplands and is of interest to a range of stakeholders.

[3] Collins et al. (2015) The Production of Quick Scoping Reviews and Evidence Assessments.
[4] http://prisma-statement.org/
[5] https://osf.io/

3.2 REA Research Questions

Based on previous work and input from the project research advisory group (RAG) the primary question proposed for the REA was: "What factors influence the behaviour of peatland users and managers, in relation to wildfire?". This represented the 'impact question' of the REA. Three secondary questions were proposed as:

i) What key factors influence management behaviours (and to what extent) in relation to **management of fuel loads and wildfire risk** (e.g. existing objectives/attitudes, prescribed burning, land use change, best practice guidance, regulation, incentives, pre-emptive risk management planning etc.) in peatlands?
ii) What key factors influence the behaviours of land managers and other peatland user groups (e.g. visitors) **in relation to sources of wildfire ignition** (e.g. access, awareness, visitor management etc.)
iii) To what extent do communication (e.g. social media or mass media campaigns) and other forms of knowledge exchange (e.g. peer-to-peer strategies) relating to wildfire risk change the behaviours of land managers and other key peatland user groups?

To further explore the REA question(s) the main elements analysed and presented using the Population/subject, Intervention, Comparator and Outcome (PICO)[6] approach of segmenting the question into specific elements (see Table 3.1). As apparent from the secondary questions and Table 3.1 the REA potentially relates to two broad user groups: land managers and other relevant peatland user groups. The REA took a primary focus on land managers, while also collating evidence relating to the general public, visitors and other users of peatlands and related areas/habitats of some relevance to the peatland context in the UK. In relation to the first secondary question, fuel load management (e.g. prescribed burning or mechanical fuel removal) is potentially affected by a broad range of factors, including indirect factors (e.g. land use change, wider land manager objectives etc.) and other complex factors (e.g. climate change) also potentially impacting on risk and subsequent behaviours. This question and related searches therefore requires careful assessment of relevance.

Table 3.1. Proposed PICO elements of the proposed REA impact question

REA Impact Question	**What factors influence the behaviour of peatland users and managers, in relation to wildfire?**
Population (The subject or unit of study)	Land managers (e.g. landowners/homeowners, gamekeepers, farmers, forest managers etc.) and other user groups (e.g. visitors) managing or using peatland areas or other areas/ habitats which may be relevant to the UK peatland context.
Intervention (The proposed **management regime, policy or related intervention** applied or investigated)	Interventions which influence land manager **behaviours and land management** and subsequent wildfire risk (i.e. fuel and fuel management)
	Interventions/communications which influence behaviours of land managers and **other user groups** in relation to **wildfire ignition risk** (including wildfire risk communications).
Comparator (The control with no intervention or an alternative to the intervention)	Altering or removing existing interventions/influences which may affect the behaviour of land managers; other users (no wildfire management/with management; before/after measures).
Outcome The effects of the intervention	Altered behaviour of land managers and/or other user groups operating in peatland areas and other related areas/habitats, relating to management or ignition factors i.e. quantifiable change

[6] See footnote 1.

	in fire risk; change in fuel loads; change in land management practices; change in user behaviours affecting risk.

Initial test searches (in Scopus) were used to further inform and refine the REA protocol. Generalised search strings and more specific targeted strings were tested to assess the numbers of articles being returned and their potential relevance to the REA question. Based on these initial searches and input from the RAG the protocol was further developed and refined, with the broad aim of identifying a relatively wide range of evidence initially and subsequently refining this list (based on the inclusion/exclusion criteria) to a shorter list for abstract review and a final list for full article review. A hierarchy (flowchart) (see Figure 3.1 in Section 3.4.1) was followed as the basis for selecting or excluding articles at different stages of the process, based on balancing the relevance/quality of identified evidence sources and the remaining knowledge gaps.

The REA questions focused from the outset on land managers and other user groups as relevant to peatland areas. However, due to relatively low search returns which were specifically focused on peatlands (e.g. studies carried out on land manager or wider user group behaviours relating to wildfire specifically in peatland areas), **the scope of the REA was subsequently broadened to include consideration of studies on land manager and user group behaviour and interventions relating to wildfire in more broadly relevant contexts,** including the uplands, prescribed burning behaviours in Europe or internationally and potentially relevant social science evidence relating to wildfires and forest fires in the US and Europe. This included evidence relating to accidental and intentional ignition in different contexts. This shift in emphasis is apparent in Table 3.1 (and in Section 3.3) in relation to the inclusion of the wording on 'other related areas/habitats relevant to the UK peatland context'. This broadening of focus facilitated the inclusion of a wider range of evidence. However, this has resulted in the inclusion of some material which is of lower direct relevance to the specific REA questions and a higher degree of uncertainty around the applicability of some of the REA findings to the UK peatland context.

3.3 REA Protocol and search results

Search strategy and key sources

The aim of the REA was to collate a comprehensive and unbiased sample of published material relevant to the primary question (and main search strategy criteria) within the project timescale. Table 3.2 shows the broad over-arching search criteria which were applied to guide the initial scope for inclusion and exclusion of evidence.

To identify relevant literature the REA applied two main approaches: i) comprehensive searches (based on specific terms and search strings specified below) using the Scopus[7] citations and abstracts search engine; and ii) a scoping approach, which incorporated website searches, contacting key authors and the stakeholder group to ask for evidence and scanning of key article reference lists for the most relevant material. In total 12 key authors were contacted and provided with specific information on the focus of the REA to acquire additional relevant evidence. The following websites of relevant research and policy organisations were also searched for relevant evidence:

[7] Scopus: https://www.elsevier.com/en-gb/solutions/scopus

- Centre for Ecology & Hydrology www.ceh.ac.uk
- Defra www.defra.gov.uk
- Environment Agency www.environment-agency.gov.uk
- Natural England (Natural England - GOV.UK (www.gov.uk))
- Knowledge for Wildfire (UK) (kfwf.org.uk))
- Nature Scot: https://www.nature.scot/
- The Heather Trust: https://www.heathertrust.co.uk/
- Moorland Forum: https://www.moorlandforum.org.uk/
- IUCN UK Peatland Programme: https://www.iucn-uk-peatlandprogramme.org/

Table 3.2 Over-arching REA search strategy criteria to define the scope of work

Scoping category	Specific criteria
Geographical reference	No restrictions were applied in relation to country of research origin/publication. This was due to literature from central/northern Europe and non-European countries (e.g. USA, Canada, Australia, New Zealand) being potentially relevant. However, **location was a factor in determining relevance scores for articles/reports** and/or as a basis for excluding sources where their relevance was low.
Language restrictions	Searches have been limited to **articles/reports published in English.**
Date restrictions	**No restrictions were applied regarding year of publication.**

Table 3.3 Keywords used for Scopus searches

Keyword category	Keywords	Secondary Keywords
Population/subject: Land managers and other peatland user groups	**Peatlands; Land manager;** gamekeeper; farmer; forest manager; ranger; public; residents; visitors	Recreationalists; recreational camping; walkers
Interventions which influence land manager **behaviours and land management** and subsequent wildfire risk (i.e. fuel and fuel management)	**Wildfire** (and/or **wild land fire**) management; fuel management; fuel load; fire breaks; fuel breaks; wildfire suppression; reduction; wildfire resilience; preparedness; response; recovery; wildfire mitigation; collaborative fire management; wildfire guidance / knowledge exchange.	Forestry and fire management/ resilience; Peatland restoration; prescribed burning; muirburn; controlled burns; land management incentives
Interventions/communications which influence behaviours of land managers and **other user groups** in relation to **wildfire ignition risk** (including wildfire risk communications).	**Wildfire ignition**; Best practice burning; wildfire management plans; wildfire education; access; fire risk awareness; visitor management; visitor behaviour; wildfire risk communications; fire setting; arson.	Visitor access; responsible access; wildfire warning systems; firewise communities.
Outcomes/impacts: Altered behaviour of land managers and/or other upland user groups relating to management or ignition factors	Wildfire/ignition risk (reduced/increased); behaviour change; improved fire awareness; reduced wildfire impact; wildfire resilience; fire plans	Reduced fire severity/extent; wildfire incidence; land use change

Search terms

The topic (title, keywords and abstract) of articles in the selected online databases was searched using specific search strings based on the keywords in Table 3.3. Keywords within each group were combined using the Boolean OR operator and between groups using the Boolean AND operator. Based on initial test searches these keywords were further refined and combined (for different parts of string searches) and a variety of searches and combined searches (e.g. land manager AND behaviour) were saved in Scopus for subsequent re-use and recombination with other saved searches (e.g. wildfire OR wildland fire). For the relevant organisational websites search strings were narrowed to a smaller selection of keywords. For Scopus search returns the first 30 search returns were scanned to determine relevance and to decide on further search combinations.

Refining the search (screening and eligibility)

To reduce and focus the amount of material identified through initial searches a specific process of applying exclusion and inclusion criteria was followed. This process and the outcomes in terms of the number of sources collated and subsequently excluded and included at each stage is shown in Figure 3.1 (Section 3.4.1).

The initial lists of search returns from applying the search terms/keywords in Scopus were collated and combined with the search results from the scoping phase (website searches, emailing authors etc.) and all duplicate search results were removed. This master list was then reduced by **applying the exclusion criteria** to article titles to eliminate non-relevant articles (screening). The exclusion criteria specified that relevant material does not include:

- Studies which are not to at least some extent relevant to behaviour and/or attitudes either of land managers or other user groups (or related to interventions which may affect the behaviours of these groups);
- Studies which relate to other forms of accidental fires distinct from wildfire;
- Studies which relate exclusively to environmental/ecological dimensions of wildfire wildfire (e.g. wildfire frequency, wildfire environmental impacts etc.);
- Studies which relate to land management/landcover more generally which do not include findings relating to manager/user behaviour.

The screening process involved two researchers independently assessing each article title. Where disagreement occurred on whether articles should be excluded these instances were discussed between the researchers to agree the outcome and the exclusion criteria were modified as required.

Following the screening phase**, the remaining articles were assessed against the inclusion criteria,** to further reduce and refine the search results. Where necessary, the full text of the article was reviewed at this stage. Additionally, the bibliographies of a small number of selected articles of high relevance were reviewed at this stage and any additional relevant sources were identified and added to the main list for review and assessment. The inclusion criteria specified that relevant material included:

- Behavioural/attitudinal studies of land managers and/or other user groups of upland/peatland areas and those operating in/using other broadly relevant areas/habitat types (potentially including prescribed burning and forest fire literature);

- Studies researching any relevant policy or management intervention which may affect land manager and other user group behaviours relating to wildfire (fuel management and wildfire ignition risk);
- Studies based on primary evidence or relevant reviews of studies based on primary evidence.

The inclusion criteria have been refined as the REA has progressed. For example, due to the limited availability of research specifically focused on/conducted in peatland areas, the inclusion criteria have been modified to allow for the potential of inclusion of studies relating to prescribed burning in other land use contexts and studies relating to land manager or other user group behaviours in wildfire/forest fire contexts in the US. A balance has therefore been struck between specificity to the REA primary question and consideration of studies of broader relevance to land manager and wider user group behaviour relating to wildfire.

Critical appraisal

The full text of articles remaining following application of the exclusion/inclusion criteria was reviewed and assessed for relevance and robustness (or excluded at the critical appraisal stage if found to be of very limited or very uncertain relevance). The relevance of articles was assessed using the criteria shown in Table 3.4, with the final scoring for this process shown in the evidence sources in Appendix 3. The robustness of the methodology and reporting was also assessed based on the criteria shown in Table 3.5, with sources which scored low across these categories excluded from the final list of evidence sources included in the REA.

Table 3.4 Matrix for assessing relevance of selected articles

Article component	**Low (1)**	**Medium (2)**	**High (3)**
Geographic location/context	Locations/countries with contrasting context/environment (e.g. US forest fire/wildfire context)	Locations with similar conditions/context to UK (e.g. upland, heathlands, Northern Europe)	UK upland context/peatland specific context or similar
Population/subject of research	Stakeholders/ broader groups (e.g. householders, public)	Partly/mixed relevance samples (e.g. not peatland specific, visitors etc.)	Upland/peatland land managers or other user groups in these contexts
Intervention/ measure/ practice	Less directly relevant measures (e.g. householder awareness)	Interventions of broader relevance (e.g. visitor awareness, land use incentives)	Directly related to replicable wildfire interventions (e.g. wildfire groups, burning regulations)
Overall score			

Table 3.5 Matrix for assessing robustness of selected articles

Article component	**Low (1)**	**Medium (2)**	**High (3)**
Objectives/Hypothesis	Lacking focused objectives	Broad objectives/ research questions	Specific focused research objectives
Methods/approach	Limited or no sample, or limited secondary data analysis	Representative sample, restricted size/quality or based on review	Large representative samples, may be multi-site or extensive review
Reporting/analysis	Minimal analysis and limited reporting, summary results and no detailed interrogation.	Some analysis, may include some quantitative. Limited interrogation of results.	Detailed analysis, reporting and interrogation of results, may include mixed methods and theory or modelling
Quality of publication	Unpublished/no clear peer review	Grey literature, no/unclear review process	Peer reviewed published article
Overall score			

Data extraction and collation

Evidence identified as relevant based on the steps outlined above was summarised and extracted into a spreadsheet template to ensure transparent recording of all relevant summary information and to provide an overview of the evidence which can be rapidly assessed. This template includes the following details for each article:

- **Full title and author(s)** including full reference, DOI/web address
- **Year/date of publication**
- **Subject of research/population** (e.g. land managers etc.) and location
- **Intervention/measures researched** (e.g. policy or management intervention etc.)
- **Methodology:** quantitative, qualitative, sample size etc.
- **Results:** summary of key study results - impact of interventions/factors on land manager or wider user group behaviours (relating to wildfire)
- **Scoring** for relevance and robustness of evidence source
- **Reviewer comments** (from research team)
- **Link to full article/report** stored as PDF on secured drive

3.4 Thematic summary of evidence

This section summarises key findings from the collated evidence. Due to the limited availability of highly relevant evidence specific to peatland contexts, many of the sources summarised below relate to evidence from more broadly relevant contexts (e.g. uplands, prescribed burning and forest fires). The main thematic topics for which evidence was collated are summarised in Tables 3.6 and 3.7, with the sub-sections providing more detail on these themes. The first section presents a concise summary of the number of sources found using the combined approaches and the results of applying the REA protocol.

3.4.1 REA Search results

The main stages of the REA process are shown in Figure 3.1, which also summarises the number of sources remaining at each stage of the process. The Scopus searching phase resulted in an initial long list of 3035 search results (with all duplicate searches removed). The REA exclusion criteria were then applied to this long list (e.g. removing natural science papers), which resulted in a reduced list of 248 sources, for which the abstract was sourced from Scopus and added to the database. The exclusion criteria were reapplied to this short list and the inclusion criteria, resulting in a shortened list of approximately 60 articles. These articles were fully reviewed and assessed by two members of the research team, with 41 of these articles subsequently selected as relevant for inclusion in the REA.

In addition to the Scopus searches, further sources were identified through the scoping process. This resulted in 69 papers, reports and articles being sourced from authors or website searches and organisational contacts and from reference list searches of key articles, with 25 of these excluded at the first exclusion stage and 30 retained following application of the inclusion criteria, with 19 of these selected for final inclusion in the REA following the full text review stage.

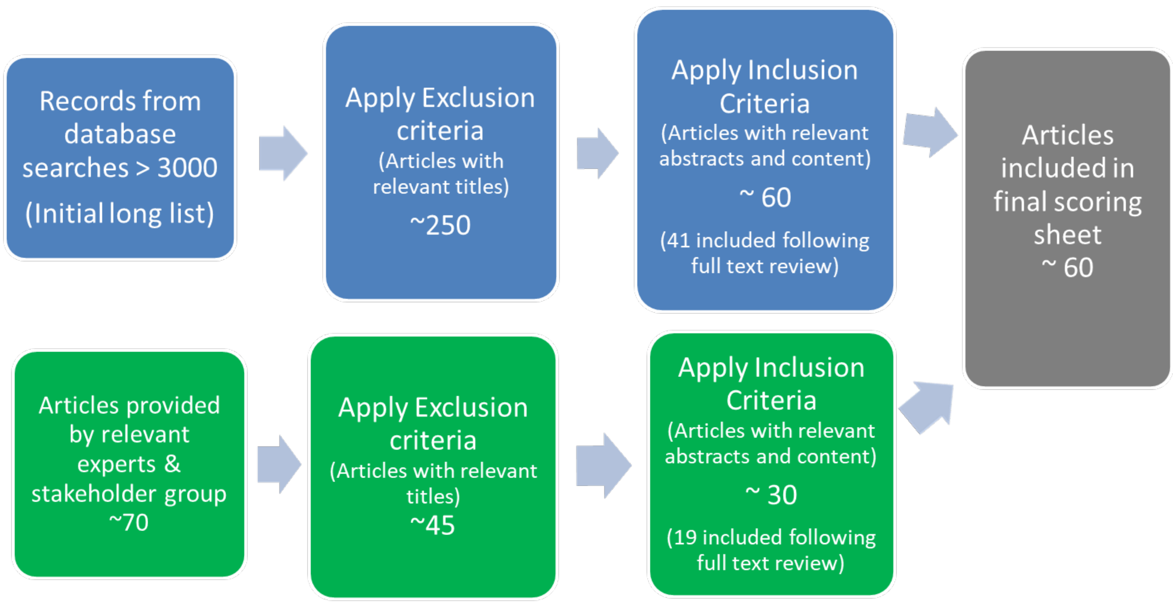

Figure 3.1. Flow chart illustrating the REA protocol and search results remaining at each stage

The combined 60 sources (from Scopus searches and the scoping phases) selected for inclusion were all scored for relevance (in relation to relevance of the subject/user group, contextual relevance and relevance of the intervention). From the 60 sources 10 scored as moderate-high relevance, 18 as moderately relevant, 27 as low-moderate relevance and 5 as being of low relevance. Articles of high relevance to the research question (e.g. studying user group behaviours in relation to wildfire specifically in peatland/upland contexts) were therefore limited, although a number of articles are relevant to specific aspects of the REA criteria (e.g. land manager behaviours in relation to fuel management). The full list of included articles and relevance scoring is shown in Appendix 3.

The final list (Appendix 3) list of sources were from a relatively wide range of journals, with a small number of journals providing multiple sources, including the Journal of Forestry (6), the International Journal of Wildland Fire (4), Ecology and Society (3), Forests (2) and Rangeland Ecology and Management (2), with four research reports/publications also included from the SCION Rural Fires Research group in New Zealand. All the sources in the list were published post-2001, with 10 published from 2001-2009, 24 from 2010-2014 and 26 since 2015. The sources were predominantly peer-reviewed journal articles, with a smaller number of research reports, and covered a range of methodologies, with the majority of studies based on primary research. The approaches/methods used included surveys of residents or land managers/owners or the public (13), case study based research (12), evidence reviews (11), interviews of focus group based studies (7), modelling (5) and mixed methods (12) approaches (including combinations of case studies, interviews, evidence review and secondary data analysis or spatial analysis).

The selected studies were from a range of contexts, with the largest number (28) related to forest/wildland fires in the US. A further 7 related to forest fire or prescribed burning in rural New Zealand and 6 were from Australian studies. Studies were also included which related to European contexts (6), uplands or peatlands in the UK (9), wildfire in Africa (1) and South America (1) and two global studies of prescribed burning practices.

As stated above, while the focus of the REA was specifically land manager (or other user groups) wildfire related behaviours in peatland contexts, the majority of studies did not relate specifically to peatlands (see Appendix 3). The main themes of the studies shown in Appendix 3 can be summarised as: i) fuel management and specifically prescribed burning and use of fire as a management tool, including studies of fire based cultural land uses and practitioner aspects (12 sources); ii) collaborative working for wildfire management, including collective values framing and decision making and management plans (9 sources); iii) wildfire communications, including fire prevention programmes, outreach and education and impacts on land manager and visitor/public attitudes and behaviours (i.e. ignition risks) (11 sources); iv) resident and homeowner/landowner perceptions of risk and adoption of wildfire mitigation measures, including aspects relating to community fire response (10 sources); v) assessment of policies and cross sectoral working and regulatory or incentives relating to wildfire management (12). Other studies included studies on modelling and broader reviews of causal factors for wildfires.

3.4.2 Behaviours and interventions relating to wildfire risk reduction and control

This section presents a summary of the first of the two main themes, focusing on behaviours and interventions related to wildfire risk reduction and control. This includes aspects related to fire suppression. Table 3.6 summarises the main themes and sub themes on wildfire risk reduction and control relevant to the REA questions and as evident from the REA results. The key findings are summarised, based on quantitative (e.g. survey), as well as qualitative evidence which is more broadly indicative of an intervention effect on behaviour.

Table 3.6 Behaviours and interventions relating to land management and wildfire risk reduction and control as evident from the collated evidence

Behaviour category	Specific Manager/ User Behaviours	Interventions
Proactive management of fuel loads/fuel reduction	Prescribed burning, and mechanical/chemical fuel removal	**Regulatory control** of prescribed burning/land uses which use burning
		Collaborative local groups of burning practitioners and stakeholders) for sharing best practice, cooperation and training
	Maintaining traditional burning regimes/land uses	**Cost sharing/incentives** for marginal land uses and/or for fuel management (by grazing or prescribed burning)
		Capacity building and advice measures/support for land managers/communities, best practice and training standards and certification.
	Public acceptability of fuel/hazard control and effects on manager behaviour	**Public education/awareness** and outreach
Fire resilient landscapes	Proactive design (fire resilience) in landscapes/ forest design; fire/fuel breaks (mitigation)	**Technical advice/guidance** and support from agencies/key stakeholders
	Fire risk planning (e.g. escape routes) in land/forest management plans	**State support for wildfire protection plans** at community/landscape scales
Wildfire preparedness	Community level wildfire preparedness (mitigation measures, emergency plans, suppression equipment etc.)	**Place-based collaboration (partnerships)** between fire management agencies/fire brigades and land managers/householders (communities) for trust building; KE on best practice.
	Use and community/stakeholder acceptance of technological solutions	**Fire early warning systems** implemented using a participatory approach to enhance acceptance/uptake
	Householder/landowner uptake of wildfire mitigation measures and related risk perceptions	**Education and outreach** on mitigation measures and fire risk management/risk perceptions
Fire suppression measures	Emphasis by land managers and agencies on suppression versus fuel management/ alternative approaches	**Adaptive and collaborative fire management approaches and flexible planning and policy approaches** to suppression; established rapid response groups.
	Community/practitioner involvement in fire management, response (suppression) and recovery	**Training opportunities** for fire managers/land managers; **training certification**; trust building between agencies and land managers.

Proactive management of fuel loads/fuel reduction

Multiple sources focus on land manager behaviours relating to prescribed burning, used either specifically to reduce fire risk (e.g. in or around forest cover) or as a component of a traditional land management system (e.g. pastoral management regimes). Evidence was also collated relating to cost sharing/incentives to support grazing systems to maintain fuel breaks and on the social acceptability of different approaches to fuel management (burning, mechanical fuel removal etc.). Notably in most cases these studies are not peatland specific and while many of the messages may be relevant to wildfire management in the UK, the contexts of the reported studies are often different (e.g. pastoral systems in Southern Europe or uptake of fuel reduction measures for forest fires in the US). Specific findings included:

- **Reduced prescribed burning** (resulting from regulation on burning timing/regularity etc.) in upland (hillfarm) contexts in Ireland is **perceived by practitioners as increasing wildfire risk** due to the increased risk of high fuel loads and increased potential for loss of control of burns (Carroll et al. 2021). Studies in Europe have also proposed **a link between the loss of cultural land uses systems (i.e. agricultural land abandonment), which utilise prescribed burning, and increased wildfire occurrence** (Coughlan, 2013; Montiel and Kraus 2010; Jajtić et al., 2019). These land use shifts are attributed to socioeconomic restructuring (e.g. changes in agricultural subsidies), resulting in landscape change (increased scrub habitat), which may can increase fuel loading and wildfire risk (Jajtić et al., 2019).
- There is evidence that the development of **stringent 'command and control' policies and increased regulation of traditional, self-organised fire-based land management systems can have potentially negative impacts for managing wildfire risk** (Huffman, 2013; Coughlan, 2013; Clifford et al., 2016; Davies et al., 2016; Carmenta et al., 2019). Instead, evidence from prescribed burning in Europe suggests an emphasis on flexible policy approaches and adaptive management based on scientific approaches and long-term monitoring, offers greater scope for understanding and enhancing the sustainability of burning practices (Fernandes et al. 2013; Montiel and Kraus, 2010; Davies et al., 2016). These findings are also reflected in research on community and household level responses to undertaking wildfire mitigation in Australia (Prior and Erikson 2013), and wildfire management in US forest systems (Steelman et al. 2011), which identified **flexible policy and planning approaches (and regular review), including regional policy adaptation, as important for increasing the ownership, uptake and sustained application of wildfire mitigation measures**, and so reduce wildfire risk.
- Paveglio et al. (2014) also concluded that **the effects of wildfire mitigation policy measures are context dependent.** In particular, they found that the integration of local knowledge and use of trusted local information sources is important to frame wildfire mitigation messages for rural communities who are more likely to adopt these where they are perceived to align with existing community identity, norms and culture (compared to suburban and rural-urban fringe communities who may be more receptive to more top-down approaches). In relation to wildfire management in the Ivory Coast, Kouassi et al. (2020) also found that policies and institutions for wildfire management were more likely to be implemented effectively when they incorporate community knowledge and utilise local networks.
- **Cost sharing and/or incentives can have a positive effect on increasing uptake of fuel reduction/treatment** measures by landowners/householders, with Bhuivan et al. (2019) concluding that targeted, risk-based allocation (i.e. where decision makers prioritise high risk land parcels for support) approaches to providing financial support are more effective for reducing risks associated with forest fires in the US. Jarrett et al. (2009) also concluded that (in a US context) awareness of wildfire programs does not always result in adoption of prevention and mitigation actions, suggesting that incentives or other forms of support are needed to enhance uptake. In relation to social barriers to the implementation of the England Peatland Strategy, Reed et al. (2020) also identified the importance of ensuring payment levels for land management measures provide genuine incentives and as a minimum cover the full economic cost of implementing changes.
- **Incentives provided for maintaining a network of fuel breaks using targeted grazing have been successful for reducing fire risk** in Southern Europe (Varela et al. 2018). This collaborative model of fire management incorporates 220 shepherds

and has demonstrated high levels of efficiency in reducing fuel loads, through supporting a traditional land use system of livestock grazing. The success of the scheme over a 15-year period has been attributed to the combination of effective fuel break maintenance (based on regular monitoring of biomass against agreed targets), long term commitment to financial incentives provision and effective collaboration and trust building between agencies and practitioners (Varela et al. 2018). Fischer et al. (2012) also concluded that the uptake and effectiveness of wildfire mitigation measures among private forest owners in the US is higher (particularly for 'commodity' focused managers), where available incentives facilitate the continuation of traditional land use systems. Reflecting this emphasis on supporting established systems, Coughlan (2013) further identified socio-economic factors which enable the continuation of traditional land uses systems as important to the retention of sustainable prescribed burning practices.

- **Public attitudes towards fuel management** can affect land manager behaviours relating to burning practices, with Carroll et al. (2021) identifying negative public perceptions as one factor responsible for a decline in the practice on hill farms in Ireland. There is also evidence relating to burning practices for fuel management in the US (Jacobsen et al. 2001) and in Europe (Carrerias et al. 2014), that consensus-based, participative approaches (which include the public and other stakeholders and account for local characteristics) are important for designing and implementing successful (and accepted) policy and legal frameworks for reducing wildfire risk. Based on a review of burning and wildfire management in the UK, Davies et al. (2008) concluded that participatory approaches to developing recommendations and regulations around prescribed burning offer greater scope for successful implementation, particularly where linked with improved fire reporting and preparedness (i.e. incident planning). Fernandes et al. (2013) concluded that **effective communication, outreach and education (including demonstration projects), were important for raising awareness of the benefits and impacts of prescribed burning.**
- The establishment (or improvement) of **national (or European) training standards for wildfire management and prescribed burning practices and technical certification** for practitioners, has also been associated with increased uptake of mitigation measures and adoption of best practice (Prior and Erikson 2013; Molina et al. 2016; Fernandes et al 2013; Davies et al. 2016). Clifford et al. (2016) and Bayne et al. (2018 and 2019) also identified a need for training and clear guidelines (and agreed protocols) around best practice in using fire safely and effectively to manage land in a rural New Zealand context. The use of training and certification for fire users has been proposed as being of increasing importance in relation to the current emphasis on adaptive management, monitoring and best practice (Montiel and Kraus, 2010).

Fire resilient landscapes

Proactive design of landscapes, particularly in relation to fire and fuel breaks, was identified as a critical aspect of wildfire mitigation, particularly in relation to forest management planning but also in relation to forest boundary areas or mosaic landscapes (e.g. Valera et al. 2018). Specific findings included:

- Based on a review of prescribed burning in different contexts across Southern Europe (including heathland and mountain shrubland) Fernandes et al. (2013) highlighted the **importance of improving spatial and temporal planning for burning regimes (using reporting systems and decision support tools), which should incorporate**

zoning landscapes to identify specific areas where unplanned fire is acceptable. This reflects the findings of Valera et al. (2018) who concluded that landscape-scale wildfire mitigation schemes (in their case a grazing system for maintaining fuel breaks) require a coordinated approach from agencies and highly effective collaboration to ensure long term success.
- Gan et al. (2015), in a study of family forestland owners in the Southern US, found that **owners who had a forest management plan (as well as those lived on their land) were significantly more likely to proactively respond to wildfire risk** by undertaking mitigation measures (e.g. fuel reduction, fuel breaks, planned escape routes etc.). The provision of support to landowners in developing management plans (i.e. with technical advice or funding from state agencies) can therefore boost wildfire mitigation and adaptation across a landscape (Gan et al. 2015; Jajtić et al., 2019). In relation to privately owned conservation landholdings in Australia, Halliday et al. (2012) concluded that property specific plans (developed collaboratively with wildfire stakeholders) could be used to **integrate ecological fire requirements into biodiversity management, while safeguarding life and property**.
- Fischer (2012) also found that **uptake of incentives for wildfire mitigation measures increased among amenity woodland owners in the US, when this was facilitated by advisors/consultants** who assisted owners in planning and implementing the work.

Wildfire preparedness and risk management

Wildfire preparedness relates to both undertaking measures to reduce the risk of wildfire (e.g. fuel reduction) and also preparing for controlling and suppressing wildfires when they occur and reducing their potential impacts for communities. In practice, this incorporates mitigation measures, emergency planning and ensuring the equipment and staff/volunteers are in place and sufficiently trained and aware of procedures. Specific findings under this theme included:

- Prior and Eriksen (2013) (in Australia) and Paveglio et al. (2019) (in the US) both identified **a strong link between community cohesion and the extent of 'social fragmentation' and levels of wildfire preparedness and risk reduction evident within communities**. In these cases, the connectivity and cohesion across a community was identified as having a direct effect on the household (and wider community) level response to undertaking wildfire preparedness measures (Prior and Erikson 2013). These authors concluded this was due to **community cohesion supporting effective decision making related to risk by individuals** and enhancing community capacities which reduce vulnerability.
- In relation to fostering the development of community cohesion and related wildfire preparedness at community level, Prior and Eriksen (2013) and Brenkert-Smith et al. (2011) highlight the **importance of local-level community consultation and collaborative action (between communities and fire management stakeholders) in relation to developing wildfire mitigation measures which recognize contextual factors and local concerns.** This reflects the discussion on the importance of collaborative, place-specific approaches below (Section 4.2.4).
- Based on a review of research on community and homeowner acceptance of wildfire mitigation measures in the US, McCaffrey et al. (2015) concluded that **timely, accurate communication and outreach** that i) involves citizens; ii) occurs at all stages (before, during, after fires); and iii) takes a partnership building approach between agencies and communities, **can increase acceptance of the need for fire management and mitigation measures among land/home owners**. In addition, these authors identify the potential for effective outreach to reduce negative emotions

and stress related to fire incidents and increase community and community-agency cohesion in relation to mitigation measures and collaborative fire responses. This reflects the findings of a synthesis of evidence on fuel management by Jakes (2007), who concluded that communication and outreach can increase uptake of mitigation measures where it incorporates consistent messaging, general social/aesthetic acceptability of mitigation treatments and occurs at different stages.

- Contrasting with the emphasis on communication and education above, based on case studies and workshops of wildfire cases in the U.S. Arvai et al. (2006) emphasized the need for **improved capability in decision making and risk management,** through the use of decision support tools and frameworks (as opposed to a focus on improving stakeholder awareness of risks or participation in wildfire programs). Studies on both prescribed burning and wildfire management have also demonstrated the potential of Agent Based Models (ABMs), to be used to support decision making processes in relation to prescribed burning practices and wildfire management/fuel reduction treatments at landscape scales (see Penman et al., 2020 and Spies et al., 2014).
- In addition, while educational interventions can affect behaviours of homeowners in the wildfire-urban interface (in the U.S.), the impact of communications and education measures can vary considerably based on previous experience of wildfires and use and knowledge of forests (Ryan, 2012; Brenkert Smith et al., 2013). Research on community perceptions of wildfire risk in New Zealand further confirmed that risk perceptions can vary and communications, education and collective actions, should account for different values and local context when addressing wildfire readiness, response and recovery.
- In relation to the role of technological solutions for enhancing wildfire responsiveness, Edgeley et al. (2016) also assessed key influences on stakeholder support for a wildfire early warning system (EWS) in a UK protected area. They determined that the level of public and wider stakeholder **acceptance and support for early warning systems was dependent on approaches to EWS implementation which facilitate shared understandings of fire hazards across stakeholders and incorporate critical consideration of pre-existing stakeholder values** and dynamics.

Collaborative activity and place-based approaches

An important theme identified in the literature in relation to both community wildfire preparedness (mitigation and suppression) and coordination of landowner activities for wildfire suppression, relates to effective **collective action**. Key findings include:

- Paveglio et al. (2021) found in the U.S that participation of private property owners in **collaborative wildfire programmes had a positive effect on their uptake of wildfire mitigation** measures.
- Carroll et al. (2021), Coughlan et al. (2001) and Fernandes et al. (2013) all identified the **importance of establishing working partnerships between land managers and key stakeholders** for facilitating shared understandings and values and building trust, disseminating best practice and knowledge and reducing wildfire risk.
- Staciewicz et al. (2018) investigated key factors influencing the establishment and functioning of Rangeland Fire Protection Associations (RFPA) in the US, based on case study analysis. They concluded that **RFPAs can foster adaptive responses and enhance wildfire responsiveness, through using a place-specific, participative approach**. The RFPA model was identified as particularly suited to mixed ownership settings, where fire was perceived as a threat to resources and where

residents had previous experience of helping each other, with limiting factors including terrain, fire experience and ageing populations (Staciewicz et al. 2018).

- This reflects findings from other studies relating to forest management (in the U.S.), which recommend the development of **place specific, tailored approaches, to facilitate shared understandings of fire hazards (i.e. trust building) and give consideration to pre-existing stakeholder** (agencies, fire brigades, land managers and the public) **values and dynamics, thereby enhancing uptake of mitigation measures through developing a common sense of purpose and commitment** (Stasiewicz et al. 2018; Sturtevant et al., 2015; Maguire and Albright 2005; Fleeger, 2008). Brooks et al. (2006) identified the **integration of collaborative capacity, problem framing (common goals and values) and trust building**, as a prerequisite of collective action to develop Community Wildfire Protection Plans, reduce fuels, enhance public safety and preparedness, and/or create defensible space. Champ et al. (2012) also emphasized the importance of accounting for differences in the way risk mitigation is framed between stakeholders and the role of power dynamics in hampering communication within collaborative partnerships to ensure effective wildfire management. This over-arching emphasis on collective action and shared values framing in the US wildfire literature is reflected in the European literature on prescribed burning (e.g. Fernandes et al. 2013), and in a recent study on social barriers and opportunities to the implementation of the England Peatland Strategy (Reed et al., 2020).
- In relation to wildfire management in a UK context, Gazzard et al. (2016) and Davies et al. (2016) both emphasized **a need for participatory solutions to developing coordinated (cross-sector) policy approaches**, with the aim of increasing understanding of burning practices and wildfire and implementation of best practice wildfire mitigation. In a U.S. forest fire context, Steen-Adams et al. (2017) also concluded that **interventions which promote the evolution of informal institutions (e.g. cultural norms and knowledge systems), in tandem with developments in policy and legislation**, can enhance decision making flexibility (and adaptive approaches) and accelerate adaptation. Maguire and Albright (2005) also identified the potential for structural and educational changes within and between stakeholder organisations to reduce perverse incentives that reward risk aversion and discourage adaptive management in relation to wildfire management. Additionally, in a comparative analysis of wildfire policy approaches in the UK and New Zealand, Moffat and Pearce (2013) identified the **potential for a greater emphasis on wildfire mitigation and development of a coherent risk management framework for wildfire in the UK** (as opposed to the current emphasis on readiness and response).
- **Training opportunities** which involve practitioners and stakeholders/agencies can have a **positive effect for trust building and adoption of mitigation measures** among land managers (Stasiewicz et al. 2018).

3.4.3 Behaviours of land managers and other user groups and interventions relating to wildfire ignition risk (accidental and intentional ignition)

The evidence collated relating to ignition (accidental or intentional) was more limited than for fuel/risk management. Table 3.7 summarises the main themes and sub themes relevant to ignition from the REA themes of enquiry and as evident from the REA search results.

Table 3.7 Behaviours and interventions relating to wildfire ignition (accidental and intentional) evident from the collated evidence

Behaviour category	Specific Manager/ User Behaviours	Interventions
Wildfire Ignition - accidental	Loss of control of prescribed burns (fire spread)	**Promotion of best practice** (intensity, timing etc.) and sufficient available staff/support and equipment
	Accidental ignition from other user groups (camping, barbecues)	**Public education/engagement on fire risk awareness** responsible fire behaviour/fire risks from accidental ignition (fire risk campaigns etc.
Wildfire Ignition - intentional	Arson/intentional fire starting	**Public wildfire education** (on wildfire arson and risks from intentional fire setting) - youth education programmes on wildfire risk/risk awareness
		Targeted education (specific groups) and local awareness and engagement programmes on wildfire risk awareness
		Police involvement in wildfire mitigation strategies and awareness programmes
		Limiting access to high risk areas (visitor management)

Human-related ignitions include those related to escaped managed burns, accidental ignitions relating to public access (campfires etc.), escaped managed burns and deliberate fire setting (arson). Key findings at this stage include:

- Glaves et al. (2020) concluded **that the majority (77%) of wildfire ignitions in the UK are anthropogenic** (accidental or arson), with a higher level classed as deliberate in the lowlands (80%) than in the uplands (55%) (although most fires (88%) were also in the lowlands). In cases where an ignition source was identified (lowlands and uplands combined) these included campfires (49%), managed burns (15%), barbeques (10%), and reignited fires and military training (5% each), although **when uplands fires were looked at in isolation (based on a limited dataset) managed burns represent a much more significant ignition source (68%)** (Glaves et al. 2020).
- Jollands et al. (2011) and McMorrow et al. (2009) identified **a link between wildfire incidence and public access/visitor behaviour, particularly on the rural-urban fringe (which represents a high-risk wildfire zone) and during busy periods.**
- Evidence from Europe and North America reinforces the finding that most wildfires are the result of human caused ignition, with key factors including visitor access, agricultural activities (and land abandonment), population density, urban development and human accessibility (Glaves et al. 2020)
- Jollands et al. (2011) concluded that **public education programmes and information dissemination in Wales have had a relatively limited impact on public perception of wildfire ignition risk**. These authors also concluded (based on the long-term persistence of arson in Wales), that the impact of general wildfire public

education programmes on arson has been limited. However, targeted participative engagement at local levels and training courses with young people (including potential arsonists) in high-risk areas can have positive outcomes for reducing ignition risk, with a 46% reduction in call out rates in one Welsh region associated with a six week programme of targeted wildfire engagement (Jollands et al. 2011). Research on wildfire communications in the US and New Zealand further emphasized the importance of targeting wildfire communications to specific groups (e.g. recreationalists or land managers) and facilitating a two-way dialogue for greater effectiveness (Langer and Hart, 2014; Vadala et al., 2012). Remenick (2018) also noted the importance of matching modes of communication with information type, with mass communication (flyers, announcements etc.) most effective for disseminating simple knowledge and integrative communication (discussions, field visits, forums, collaborative efforts etc.) more effective for detailed knowledge exchange and in relation to influencing opinions and behaviours. In addition, long term trust building can play an important role, with Olsen and Schindler (2010) identifying that positive citizen-agency relations require a long-term approach, to ensure key stakeholders are supported by communities during and after wildfire events.

- In a study on public behaviour relating to forest fires in the US, Martin et al. (2011) concluded that **direct (face to face) communications, continuous and consistent messaging and tailored education programmes**, can enhance risk reduction activities and reduce ignition risks. Research on wildfire communications in New Zealand found that activities with high ignition risks, such as prescribed burning, campfires, barbeques and smoking, can be managed by effective communication (Scion, 2011). This should avoid overly complex aspects (with the public found to have a poor understanding of the Fire Danger Rating tool), and focus on using universal symbols, clear warning signs, engaging public campaigns (e.g. with a cartoon character), tv and radio adverts and social media (Scion, 2011; Grant et al., 2017). Martin et al. (2011) also identified the importance of timing for risk reduction messages (and the idea of 'teachable moments' immediately after fires). This reflects the emphasis by McCaffrey et al. (2015) and Jakes (2007) (above) on interactive education at all stages (before, during and after fire events) for increasing acceptance of wildfire risk. Olsen and Schindler (2010) also identified that positive citizen-agency relations require a long-term approach, to ensure key stakeholders are supported by communities during and after wildfire events.
- Jollands et al. (2011) identified **a link between police involvement in wildfire awareness campaigns and youth initiatives and levels of wildfire incidence.** This included the example of a partnership developed between Dorset Police (and prioritisation of wildfire in target areas by the local police using an operational order) with the local Fire and Rescue Service and council (the 'Urban Heath Partnership'), which has resulted in a marked decrease (60%) in heathland fires in the region. In a U.S. wildland fires context Abt et al. (2015) also concluded that the involvement of law enforcement in wildfire prevention programs had a beneficial effect on reducing ignition risk behaviours, such as escaped campfires and juvenile fire setting.

3.5 Knowledge gaps, key messages and future research needs

Limitations of the evidence and key messages

While the key messages from much of the literature referred to here are broadly (or in some cases directly) relevant, it should be noted that many of the referenced studies do not relate specifically to research which has been carried out in UK peatland contexts. In addition, social science research relating to wildfire management (either related to fuel management or ignition behaviours) in the UK is relatively limited. The scoping element of the REA process has therefore been important in relation to identifying relevant studies from a limited evidence base and studies of broader relevance to the REA questions. In a number of cases the evidence relates more specifically to prescribed burning (e.g. pastoral burning) or forest wildfires in Europe or the US. In these cases, while the general findings may be relevant, the environmental context may be very different, which suggests a high degree of uncertainty in terms of directly transferring the implications of key findings and specific recommendations to the UK peatlands context. For example, while many of the studies relating to prescribed burning in Europe (which include burning in upland/heathland contexts) are broadly relevant to upland land management in the UK, land manager behaviours relating to prescribed burning are less relevant to areas where no burning is occurring (for fuel reduction or other reasons) due to regulatory constraints or changes in land management. In addition, while some studies relate to a specific intervention and related effects on manager/user behaviours, some are more qualitative or review-based and determining specific 'outcomes' and applying these within a modelling framework is more challenging in these cases.

Despite these evidence gaps and uncertainties some over-arching concluding themes can be identified from the REA process at this stage. These include:

- The development of **stringent 'command and control' policies and increased regulation of traditional, self-organised fire-based land management systems can have potentially negative impacts for managing wildfire risk.** Instead, evidence from prescribed burning in Europe and wildfire management in US forest systems, **suggest that flexible policy and planning approaches (and regular review), including regional policy adaptation** can increase the ownership, uptake and sustained application of wildfire mitigation measures and so reduce wildfire risk.
- The **effects of wildfire mitigation policy measures are context dependent**. In particular, they the integration of local knowledge and use of trusted local information sources is important to frame wildfire mitigation messages for rural communities who are more likely to adopt these where they are perceived to align with existing community identity, norms and culture (compared to suburban and rural-urban fringe communities who may be more receptive to more top-down approaches).
- In European and international contexts the **continuation of traditional land use systems has been identified as important to the retention of sustainable prescribed burning practices** over the long term (in specific land use contexts). In addition, extensive monitored and incentivized grazing schemes case be used effectively for managing fuel breaks (using a payment for ecosystem services model) in specific contexts.
- **Public attitudes towards fuel management can affect land manager behaviours relating to fuel management and burning practices.** Effective communication, promotion and education (including demonstration projects) are therefore important for raising awareness of the benefits and impacts of controlled burning among policy makers and the public.

- Temporal and spatial planning and land and forest **management plans which incorporate fire risk planning components, offer potential for enhancing hazard awareness and mitigating wildfire risk.**
- Connectivity and cohesion across a community can have a direct effect on community-level responses to undertaking wildfire preparedness measures. This is due to community **cohesion supporting effective decision making related to risk by individuals** and enhancing community capacities which reduce vulnerability.
- The development of **place specific, collaborative, community wildfire programmes** can have positive effects for mitigating wildfire risk at community and landscape levels. These may include, for example, collaborative development of land management plans and training. While the literature emphasizes the need for skills and knowledge to be place-specific, **national training standards and certification has also been associated with increased uptake of mitigation measures** and adoption of best practice. With effective facilitation, community programmes may enable resource-pooling and planned collaborative responses to wildfire. This may increase the likelihood of a rapid response to wildfire, and by building a common sense of purpose linked to shared values and understandings of hazards, may enhance uptake of mitigation measures.
- Public education programmes and information dissemination have an important but limited impact on public perception of wildfire ignition risk. Communication and outreach that: **i) involves citizens (i.e. is interactive/participative); ii) occurs at all stages (before, during, after fires); iii) uses consistent messaging; iv) employs a tailored placed-based approach for high risk areas; and v) takes a partnership building approach** between agencies and communities, can increase acceptance of wildfire policy and regulatory frameworks and adoption of wildfire mitigation measures on the part of land managers and the wider public.
- **Police involvement in wildfire awareness campaigns and youth initiatives** (and prioritisation of wildfire as an issue at local levels by police forces) offers potential for increasing the impact of outreach programmes and reducing wildfire risk.

Potential future areas of enquiry

In broad terms, evidence relating to land manager and wider user group behaviours in the UK relating to wildfire (fuel and risk management, fire control and ignition), and related to wildfire policy or management interventions, represents a knowledge gap – particularly in relation to studies directly relevant to peatland areas. More specific key areas of future investigation within this broad theme include:

i) **Existing collaborative fire management groups** in the UK, including in mixed ownership/context and high value landscapes (e.g. National Parks). To include investigating the governance, current functioning and effectiveness (in terms of fuel management/ignition risk reduction behaviours), resourcing and knowledge sharing roles of these groups.

ii) **The perceptions, attitudes and practices** of key peatland user groups (e.g. conservation land managers, farmers, gamekeepers, crofters) in relation to burning practices and (motivations/values and cultural dimensions) and in relation to wildfire mitigation practices in the UK.

iii) Assessing **user group values and practices in relation to land use trajectories and scenarios in upland/peatland areas**. To include assessing the implications of user values/cultural practices for wildfire policy implementation, including potential regulatory change, incentives and knowledge transfer.

iv) **Determining public attitudes towards wildfire risk awareness in rural and peri-urban** (urban/rural interface) contexts and in high risk/protected areas and the potential/actual impacts of different forms of fire risk education and engagement on ignition risks in different user groups.

v) **Assessing causal factors/drivers for intentional fire setting** in different contexts (upland, lowland, peatlands) in the UK and the impacts of interventions (outreach, education etc.) on intentional ignition risks.

Appendices

Appendix 1: Strength of influence analysis

Strength of influence is calculated from the CPT of the child node and expresses a statistical distance (or strength of relationship) between the conditional probability distributions over the child node conditional on the states of the parent node.

Child node	Parent node	Average	Maximum	Weighted
Accidental ignition (linked to urbanisation and managed burning)	Managed burning	0.46	0.84	0.46
Accidental ignition (linked to urbanisation and managed burning)	Urbanisation pressure	0.46	0.84	0.46
Arable condition	Artificial fertilizer	0.20	0.40	0.20
Arable condition	Drainage	0.20	0.40	0.20
Arable condition	Mean seasonal temperature change C	0.02	0.07	0.02
Arable condition	Pesticides	0.20	0.40	0.20
Arable extent	Enhance boundary & linear	0.73	0.73	0.73
Artificial fertilizer	Scenario	0.71	0.88	0.71
Biomass - animals	Improved grassland condition	0.34	0.86	0.34
Biomass - animals	Seminatural grassland condition	0.34	0.86	0.34
Biomass - animals	Shrub heath condition	0.34	0.86	0.34
Biomass - crops	Arable condition	0.48	0.86	0.48
Biomass - crops	Arable extent	0.48	0.86	0.48
Biomass woodland	Woodland overall	0.45	0.48	0.45
Bog extent	Bog restoration	0.24	0.86	0.24
Bog extent	Grouse - tracks	0.24	0.86	0.24
Bog extent	Landscape protection	0.24	0.86	0.24
Bog extent	Planting of conifers	0.21	0.80	0.21
Bog overall	Bog extent	0.50	0.50	0.50
Bog overall	Bogs condition	0.50	0.50	0.50
Bog re-wetting	Scenario	0.44	0.88	0.44
Bog restoration	Scenario	0.44	0.88	0.44
Bogs condition	Bog re-wetting	0.08	0.86	0.08
Bogs condition	Grazing intensity	0.17	0.77	0.17
Bogs condition	Grouse - tracks	0.08	0.86	0.08
Bogs condition	Landscape protection	0.08	0.86	0.08
Bogs condition	Managed burning	0.06	0.73	0.06
Bogs condition	Mean seasonal precipitation change %	0.08	0.86	0.08
Bogs condition	Mean seasonal temperature change C	0.08	0.86	0.08
Bogs condition	Nutrient enrichment	0.12	0.76	0.12
Bogs condition	Urbanisation pressure	0.12	0.76	0.12
Boundary & Linear condition	Enhance boundary & linear	0.32	0.86	0.32
Boundary & Linear condition	Landscape protection	0.27	0.73	0.27
Boundary & Linear condition	Sheep grazing intensity	0.27	0.73	0.27

Boundary & Linear extent	Enhance boundary & linear	0.48	0.86	0.48
Boundary & Linear extent	Landscape protection	0.42	0.73	0.42
Boundary & linear overall	Boundary & Linear condition	0.50	0.50	0.50
Boundary & linear overall	Boundary & Linear extent	0.50	0.50	0.50
Bracken extent	Cattle grazing intensity	0.32	0.48	0.32
Bracken extent	Planting of broadleaf	0.03	0.07	0.03
Bracken extent	Planting of conifers	0.23	0.44	0.23
Broadleaved woodland condition	Grazing intensity	0.53	0.77	0.53
Broadleaved woodland condition	Landscape protection	0.38	0.86	0.38
Broadleaved woodland extent	Landscape protection	0.32	0.86	0.32
Broadleaved woodland extent	Planting of broadleaf	0.32	0.86	0.32
Broadleaved woodland extent	Planting of conifers	0.32	0.86	0.32
Carbon value	Climate regulation	0.67	1.00	0.67
Cattle grazing intensity	Scenario	0.44	0.88	0.44
Climate regulation	Bog overall	0.15	0.48	0.15
Climate regulation	Fire reduction potential	0.15	0.48	0.15
Climate regulation	Seminatural grassland overall	0.15	0.48	0.15
Climate regulation	Shrub heath overall	0.15	0.48	0.15
Climate regulation	Woodland overall	0.12	0.44	0.12
Coniferous woodland extent	Bog restoration	0.03	0.09	0.03
Coniferous woodland extent	Planting of broadleaf	0.30	0.48	0.30
Coniferous woodland extent	Planting of conifers	0.30	0.48	0.30
Cultural services	Bogs condition	0.10	0.48	0.10
Cultural services	Boundary & Linear condition	0.10	0.48	0.10
Cultural services	Fen, marsh & swamp condition	0.10	0.48	0.10
Cultural services	Freshwater condition	0.10	0.48	0.10
Cultural services	Montane and rock condition	0.10	0.48	0.10
Cultural services	Seminatural grassland extent	0.10	0.48	0.10
Cultural services	Shrub heath condition	0.10	0.48	0.10
Cultural services	Woodland extent	0.04	0.39	0.04
Deer grazing intensity	Scenario	0.44	0.88	0.44
Drainage	Scenario	0.71	0.88	0.71
Driking water quality	Water filtering	0.67	1.00	0.67
Enhance boundary & linear	Scenario	0.71	0.88	0.71
Environmental water quality	Water filtering	0.67	1.00	0.67
Fen, marsh & swamp condition	Artificial fertilizer	0.10	0.73	0.10
Fen, marsh & swamp condition	Drainage	0.13	0.80	0.13
Fen, marsh & swamp condition	Grazing intensity	0.10	0.73	0.10
Fen, marsh & swamp condition	Landscape protection	0.12	0.86	0.12
Fen, marsh & swamp condition	Mean seasonal precipitation change %	0.12	0.86	0.12
Fen, marsh & swamp condition	Nutrient enrichment	0.19	0.76	0.19
Fen, marsh & swamp condition	Urbanisation pressure	0.10	0.73	0.10
Fen, marsh & swamp extent	Drainage	0.41	0.80	0.41
Fen, marsh & swamp extent	Landscape protection	0.52	0.86	0.52

Fen, marsh & swamp overall	Fen, marsh & swamp condition	0.50	0.50	0.50
Fen, marsh & swamp overall	Fen, marsh & swamp extent	0.50	0.50	0.50
Fire danger	Ignition source	0.51	0.94	0.51
Fire danger	Propagation	0.51	0.94	0.51
Fire reduction potential	Fire danger	0.50	0.91	0.50
Fire reduction potential	Fuel type amount related to habitat extent	0.50	0.91	0.50
Flood mitigation	Bogs condition	0.18	0.83	0.18
Flood mitigation	Boundary & linear overall	0.16	0.86	0.16
Flood mitigation	Fen, marsh & swamp overall	0.16	0.86	0.16
Flood mitigation	Seminatural grassland overall	0.16	0.86	0.16
Flood mitigation	Shrub heath overall	0.16	0.86	0.16
Flood mitigation	Woodland overall	0.10	0.62	0.10
Flood protection utility	Flood mitigation	0.67	1.00	0.67
Freshwater condition	Rivers & stream condition	0.50	0.50	0.50
Freshwater condition	Standing water & canals condition	0.50	0.50	0.50
Fuel	Biomass woodland	0.67	1.00	0.67
Fuel amount related to condition	Bogs condition	0.18	0.86	0.18
Fuel amount related to condition	Seminatural grassland condition	0.30	0.90	0.30
Fuel amount related to condition	Shrub heath condition	0.30	0.90	0.30
Fuel amount related to condition	Woodland condition	0.18	0.86	0.18
Fuel connectivity	Grazing intensity	0.51	0.94	0.51
Fuel connectivity	Managed burning	0.51	0.94	0.51
Fuel moisture	Mean seasonal precipitation change %	0.32	0.86	0.32
Fuel moisture	Mean seasonal temperature change C	0.32	0.86	0.32
Fuel moisture	Specific humidity change %	0.32	0.86	0.32
Fuel type amount related to habitat extent	Bog extent	0.18	0.86	0.18
Fuel type amount related to habitat extent	Seminatural grassland extent	0.30	0.90	0.30
Fuel type amount related to habitat extent	Shrub heath extent	0.30	0.90	0.30
Fuel type amount related to habitat extent	Woodland extent	0.18	0.86	0.18
Grazing intensity	Cattle grazing intensity	0.35	1.00	0.35
Grazing intensity	Deer grazing intensity	0.35	1.00	0.35
Grazing intensity	Sheep grazing intensity	0.35	1.00	0.35
Grouse - tracks	Scenario	0.71	0.88	0.71
Grouse shooting	Maintaining nursey populations & habs	0.67	1.00	0.67
Hay	Scenario	0.44	0.88	0.44
Health service	Driking water quality	-3.00	-3.00	-3.00
Health service	Flood protection utility	-3.00	-3.00	-3.00
Health service	Recreation	-3.00	-3.00	-3.00
Ignition source	Accidental ignition (linked to urbanisation and managed burning)	0.11	0.18	0.11
Ignition source	Intentional ignition	0.34	0.41	0.34
Ignition source	Lightning	0.01	0.01	0.01
Improved grassland condition	Artificial fertilizer	0.12	0.73	0.12

Improved grassland condition	Drainage	0.12	0.73	0.12
Improved grassland condition	Grazing intensity	0.21	0.76	0.21
Improved grassland condition	Pesticides	0.12	0.73	0.12
Improved grassland condition	Silage	0.14	0.86	0.14
Improved grassland condition	Slurry application	0.12	0.73	0.12
Improved grassland extent	Enhance boundary & linear	0.20	0.73	0.20
Improved grassland extent	Planting of broadleaf	0.20	0.73	0.20
Improved grassland extent	Planting of conifers	0.20	0.73	0.20
Improved grassland extent	Silage	0.24	0.86	0.24
Inland rock condition	Landscape protection	0.21	0.86	0.21
Inland rock condition	Mean seasonal temperature change C	0.18	0.73	0.18
Inland rock condition	Sheep grazing intensity	0.21	0.86	0.21
Inland rock condition	Urbanisation pressure	0.29	0.76	0.29
Inland rock extent	Landscape protection	0.82	0.86	0.82
Intentional ignition	Behaviour	0.37	0.63	0.37
Landscape protection	Scenario	0.58	0.88	0.58
Livestock farming	Biomass - animals	0.67	1.00	0.67
Maintaining nursey populations & habs	Bog overall	0.18	0.48	0.18
Maintaining nursey populations & habs	Boundary & linear overall	0.18	0.48	0.18
Maintaining nursey populations & habs	Freshwater condition	0.18	0.48	0.18
Maintaining nursey populations & habs	Seminatural grassland overall	0.02	0.09	0.02
Maintaining nursey populations & habs	Shrub heath overall	0.18	0.48	0.18
Managed burning	Scenario	0.71	0.88	0.71
Mass events	Scenario	0.44	0.88	0.44
Mass stabilisation & erosion control	Bogs condition	0.18	0.48	0.18
Mass stabilisation & erosion control	Boundary & linear overall	0.02	0.09	0.02
Mass stabilisation & erosion control	Seminatural grassland overall	0.18	0.48	0.18
Mass stabilisation & erosion control	Shrub heath condition	0.18	0.48	0.18
Mass stabilisation & erosion control	Woodland extent	0.11	0.34	0.11
Mean seasonal precipitation change %	Emissions scenario	0.06	0.09	0.06
Mean seasonal precipitation change %	Season	0.43	0.46	0.43
Mean seasonal temperature change C	Emissions scenario	0.06	0.12	0.06
Mean seasonal temperature change C	Season	0.20	0.25	0.20
Montane & rock extent	Inland rock extent	0.50	0.50	0.50
Montane & rock extent	Montane habitat extent	0.50	0.50	0.50
Montane and rock condition	Inland rock condition	0.50	0.50	0.50
Montane and rock condition	Montane habitat condition	0.50	0.50	0.50
Montane habitat condition	Landscape protection	0.28	0.86	0.28
Montane habitat condition	Sheep grazing intensity	0.24	0.73	0.24
Montane habitat condition	Urbanisation pressure	0.36	0.76	0.36
Montane habitat extent	Landscape protection	0.48	0.86	0.48
Montane habitat extent	Mean seasonal temperature change C	0.48	0.86	0.48
Nutrient enrichment	N deposition	0.54	0.99	0.54
Nutrient enrichment	Slurry application	0.54	0.99	0.54

Pest & disease control	Boundary & Linear condition	0.82	0.86	0.82
Pesticides	Scenario	0.67	0.88	0.67
Planting of broadleaf	Scenario	0.71	0.88	0.71
Planting of conifers	Scenario	0.42	0.84	0.42
Pollination	Boundary & Linear condition	0.24	0.86	0.24
Pollination	Montane habitat condition	0.24	0.86	0.24
Pollination	Pollination	0.67	1.00	0.67
Pollination	Seminatural grassland overall	0.24	0.86	0.24
Pollination	Shrub heath overall	0.24	0.86	0.24
Propagation	Fuel amount related to condition	0.32	0.86	0.32
Propagation	Fuel connectivity	0.32	0.86	0.32
Propagation	Fuel moisture	0.32	0.86	0.32
Recreation	Cultural services	0.67	1.00	0.67
Recreation	Scenario	0.71	0.88	0.71
Rivers & stream condition	Artificial fertilizer	0.10	0.40	0.10
Rivers & stream condition	Drainage	0.12	0.48	0.12
Rivers & stream condition	Grazing intensity	0.10	0.40	0.10
Rivers & stream condition	Mean seasonal precipitation change %	0.01	0.07	0.01
Rivers & stream condition	Mean seasonal temperature change C	0.11	0.44	0.11
Rivers & stream condition	Nutrient enrichment	0.19	0.53	0.19
Rivers & stream condition	Pesticides	0.10	0.40	0.10
Seminatural grassland condition	Artificial fertilizer	0.09	0.86	0.09
Seminatural grassland condition	Grazing intensity	0.14	0.76	0.14
Seminatural grassland condition	Hay	0.09	0.86	0.09
Seminatural grassland condition	Landscape protection	0.09	0.86	0.09
Seminatural grassland condition	Managed burning	0.07	0.73	0.07
Seminatural grassland condition	Mean seasonal temperature change C	0.07	0.73	0.07
Seminatural grassland condition	Pesticides	0.09	0.86	0.09
Seminatural grassland condition	Slurry application	0.09	0.86	0.09
Seminatural grassland condition	Urbanisation pressure	0.14	0.76	0.14
Seminatural grassland extent	Hay	0.19	0.86	0.19
Seminatural grassland extent	Landscape protection	0.19	0.86	0.19
Seminatural grassland extent	Planting of broadleaf	0.16	0.73	0.16
Seminatural grassland extent	Planting of conifers	0.16	0.73	0.16
Seminatural grassland extent	Silage	0.19	0.86	0.19
Seminatural grassland overall	Seminatural grassland condition	0.50	0.50	0.50
Seminatural grassland overall	Seminatural grassland extent	0.50	0.50	0.50
Sheep grazing intensity	Scenario	0.58	0.88	0.58
Shooting & fishing	Cultural services	0.67	1.00	0.67
Shrub heath condition	Grazing intensity	0.20	0.85	0.20
Shrub heath condition	Grouse - tracks	0.08	0.86	0.08
Shrub heath condition	Landscape protection	0.08	0.86	0.08
Shrub heath condition	Managed burning	0.07	0.73	0.07
Shrub heath condition	Mean seasonal precipitation change %	0.08	0.86	0.08

Shrub heath condition	Mean seasonal temperature change C	0.08	0.86	0.08
Shrub heath condition	Nutrient enrichment	0.13	0.76	0.13
Shrub heath condition	Urbanisation pressure	0.13	0.76	0.13
Shrub heath extent	Grouse - tracks	0.31	0.48	0.31
Shrub heath extent	Landscape protection	0.31	0.48	0.31
Shrub heath overall	Shrub heath condition	0.50	0.50	0.50
Shrub heath overall	Shrub heath extent	0.50	0.50	0.50
Silage	Scenario	0.67	0.88	0.67
Slurry application	Scenario	0.71	0.88	0.71
Specific humidity change %	Emissions scenario	0.05	0.06	0.05
Specific humidity change %	Season	0.07	0.08	0.07
Standing water & canals condition	Artificial fertilizer	0.12	0.73	0.12
Standing water & canals condition	Drainage	0.14	0.86	0.14
Standing water & canals condition	Grazing intensity	0.12	0.73	0.12
Standing water & canals condition	Nutrient enrichment	0.25	0.90	0.25
Standing water & canals condition	Pesticides	0.12	0.73	0.12
Standing water & canals condition	Urbanisation pressure	0.12	0.73	0.12
Timber	Biomass woodland	0.67	1.00	0.67
Tourism	Cultural services	0.67	1.00	0.67
Urbanisation pressure	Mass events	0.55	0.99	0.55
Urbanisation pressure	Recreation	0.55	0.99	0.55
Water filtering	Bog overall	0.15	0.48	0.15
Water filtering	Fen, marsh & swamp overall	0.15	0.48	0.15
Water filtering	Seminatural grassland overall	0.15	0.48	0.15
Water filtering	Shrub heath overall	0.15	0.48	0.15
Water filtering	Woodland overall	0.09	0.34	0.09
Woodland condition	Broadleaved woodland condition	0.54	0.99	0.54
Woodland condition	Coniferous woodland condition	0.54	0.99	0.54
Woodland extent	Bog restoration	0.31	0.79	0.31
Woodland extent	Broadleaved woodland extent	0.35	0.99	0.35
Woodland extent	Coniferous woodland extent	0.35	0.99	0.35
Woodland overall	Woodland condition	0.50	0.50	0.50
Woodland overall	Woodland extent	0.50	0.50	0.50

Appendix 2: Comparison of relationships between management and habitats included in the original Logic Map and the BBN model

The table below shows the differences between relationships included in the original Logic map (Reed et al., 2020) that were based on Bunce et al. (2018a) and those included in the BBN model in response to stakeholder feedback. Yellow fields show additions, while omissions are shown as 'removed'.

Management and	Increase (+)/	Broadleaved woodland	Conifer woodland	Boundary & linear	Arable	Improved grassland	Seminatural grassland	Bracken	Dwarf shrub heath	Fen, marsh, swamp	Bog	Montane habitats	Inland rock	Open water & canal	Rivers & streams
Sheep grazing intensity	+	C--		**C-**		**C-**	C-		C-	C-	C-	C-	**C--**		
	-	C++		**C+**		**C+**	C+		C+	C+	C+	C+	**C++**		
Cattle grazing intensity	+	C-				**C-**	**C-**	E--	C-	C-	**C-**				
	-	C+				**C+**	**C+**	E++	C+	C+	**C+**				
Deer grazing intensity	+	**C-**							C-		C-				
	-	**C+**							C+		C+				
Grazing intensity	+	C-				C-	C-		C--	C-	C-			**C-**	**C-**
	-	C+				C+	C+		C+	C+	C+			**C+**	**C+**
Pesticides/herbicides	+				C+	C+	C--							**C-**	**C-**
	-				C-	C-	C++							**C+**	**C+**
Artificial fertiliser	+				C+	C+	C*--			C-				C-	C-
	-				C-	C-	C+			C+				C+	C+
Silage	+					E++	E--								
	-					C--	E++								

Management and	Increase (+)/ decrease (-)	Broadleaved woodland	Conifer woodland	Boundary & linear	Arable	Improved grassland	Seminatural grassland	Bracken	Dwarf shrub heath	Fen, marsh, swamp	Bog	Montane habitats	Inland rock	Open water & canal	Rivers & streams
Hay	+					Removed	CE++								
	-					Removed	CE--								
Drainage	+					C+				E--	Removed			C--	C--
	-					C-				C++	Removed			C++	C++
Managed burning	+						C-		C-		C-				
	-						C+		C+		C+				
Grouse - tracks	+								CE--		CE--				
	-								CE++		CE++				
Planting of broadleaf	+	E++	E--			E-	E-	E-							
	-	E--	E++			E+	E+	E+							
Planting of conifer	+	E--	E++			E-	E-	E-			E-				
	-	E++	E--			E+	E+	E+			E+				
Landscape protection	+	C++		CE+			CE++		CE++	CE++	CE++	CE++	CE++		
	-	CE--		CE-			CE--		CE--	CE--	CE--	CE--	CE--		
Bog restoration	+		E--								E++				
	-		E++								E--				
Bog re-wetting	+										C++				
	-										C--				
Enhancing boundary & linear	+			CE++	E-	E-									

Management and	Increase (+)/	Broadleaved woodland	Conifer woodland	Boundary & linear	Arable	Improved grassland	Seminatural grassland	Bracken	Dwarf shrub heath	Fen, marsh, swamp	Bog	Montane habitats	Inland rock	Open water & canal	Rivers & streams
	-			CE--	E +	E+									
Mass events	+						C-		C-	C-	C-	C-	C-	C-	
	-						C+		C+	C+	C+	C+	C+	C+	
Recreation	+						C-		C-		C-	C-	C-		
	-						C+		C+		C+	C+	C+		
Urbanisation pressure	+						C-		C-	C-	C-	C-	C-	C-	
	-						C+		C+	C+	C+	C+	C+	C+	
N deposition	+								C-	C-	C-			C-	C-
	-								C+	C+	C+			C+	C+
Slurry application	+					**C+**	C--		C-	C-	C-			C--	C-
	-					**C-**	C++		C+	C+	C+			C++	C+
Nutrient enrichment	+								C-	C-	C-			C*-	C-
	-								C+	C+	C+			C*+	C+
Mean seasonal temperature change	+	**Removed**			C-		C-		C--		C--	E--	C-		**C-**
Mean seasonal precipitation change	+								C++	**C++**	**C++**				**CE+**
	-								C--	**C--**	**C--**				**CE-**
	-								C--	**C--**	**C--**				**CE-**

Appendix 3: Current database of evidence under review and review status

Authors	Year	Title	Source	Relevance scoring			
				User group/ Subject	Context	Inter-vention	Overall
Abt K.L., Butry D.T., Prestemon J.P., Scranton S.	2015	Effect of fire prevention programs on accidental and incendiary wildfires on tribal lands in the United States	International Journal of Wildland Fire	Mod	Low	High	Mod-High
Arvai J., Gregory R., Ohlson D., Blackwell B., Gray R.	2006	Letdowns, wake-up calls, and constructed preferences: People's responses to fuel and wildfire risks	Journal of Forestry	Low	Low	Mod	Low
Bayne, K.; Wallace, H; Parker, R; Bailey, B	2018	Improving safety at controlled burns through land manager knowledge and practices	Scion Report to Fire and Emergency New Zealand - Reserach Report number 164	Mod	Mod	Low-Mod	Low-Mod
Bayne, K.M., Clifford, V.R., Baillie, B.R., Pearce, H.G.	2019	Fire as a Land Management Tool: Rural Sector Perceptions of Burn-off Practice in New Zealand	Rangeland Ecology and Management	Mod	Mod	Mod	Mod
Bhuiyan, T.H., Moseley, M.C., Medal, H.R., Rashidi, E., Grala, R.K.	2019	A stochastic programming model with endogenous uncertainty for incentivizing fuel reduction treatment under uncertain landowner behavior	European Journal of Operational Research	Low	Low	Mod	Low-Mod
Brenkert-Smith H., Dickinson K.L., Champ P.A., Flores N.	2013	Social Amplification of Wildfire Risk: The Role of Social Interactions and Information Sources	Risk Analysis	Low	Low	Mod	Low-Mod
Brenkert-Smith, H.	2011	Homeowners' perspectives on the parcel Approach to wildland fire Mitigation: The role of community context in two Colorado communities	Journal of Forestry	Low	Low	Mod	Low-Mod
Brooks, J.J., Bujak, A.N., Champ, J.G., Williams, D.R.	2006	Collaborative capacity, problem framing, and mutual trust in addressing the wildland fire social problem: An annotated reading list	USDA Forest Service - General Technical Report RMRS-GTR	Low	Low	Mod	Low-Mod
Carmenta, R., Coudel, E., Steward, A.M.	2019	Forbidden fire: Does criminalising fire hinder conservation efforts in swidden landscapes of the Brazilian Amazon?	Geographical Journal	Low	Low	Mod	Low-Mod
Carreiras, M., Ferreira, A.J.D., Valente, S., Feskens, L., Gonzales-Pelayo, O., Rubio, J.L., Stoof, C.R., Coelho, C.O.A., Ferreira, C., Ritsema, C.	2014	Comparative analysis of policies to deal with wildfire risk.	Land Degradation & Development, 25, 1, 92–103.	Low	Low	Low-Mod	Low-Mod
Carroll, M.S., Edgeley, C.M. and Nugent, C. (2021)	2021	Traditional Use of Field Burning in Ireland: History, Culture and Contemporary Practice in the Uplands		Mod-High	Mod-High	High	Mod-High

Champ J.G., Brooks J.J., Williams D.R.	2012	Stakeholder understandings of wildfire mitigation: A case of shared and contested meanings	Environmental Management	Low	Low	Mod	Low-Mod
Clifford, V; Bayne, K; Baillie, B; Strand, T; Bader, M; Pearce, G	2016	Use of fire as a land management tool - summary document	Scion Report number 22982	Mod	Low-Mod	Mod	Mod
Coughlan M.R.	2013	Errakina: Pastoral fire use and landscape memory in the basque region of the French western pyrenees	Journal of Ethnobiology	Mod	Low-Mod	Mod	Mod
Davies, G.M., Gray, A., Hamilton, A., Legg, C.J.	2008	The future of fire management in the British uplands	International Journal of Biodiversity Science and Management	Mod-High	Mod	Mod-High	Mod-High
Davies, G.M., Kettridge, N., Stoof, C.R., Gray, A., Ascoli, D., Fernandes, P.M., Marrs, R., Allen, K.A., Doerr, S.H., Clay, G.D., McMorrow, J., Vandvik, V.	2016	The role of fire in UK peatland and moorland management: The need for informed, unbiased debate	Philosophical Transactions of the Royal Society B: Biological Sciences	Mod-High	Mod	Mod-High	Mod-High
Edgeley, C.M. and Paveglio, T.B.	2016	Influences on stakeholder support for a wildfire early warning system in a UK protected area.	Environmental Hazards, 15(4), 327–342.	Mod-High	Mod	Mod-High	Mod
Fernandes P.M., Davies G.M., Ascoli D., Fernández C., Moreira F., Rigolot E., Stoof C.R., Vega J.A., Molina D.	2013	Prescribed burning in southern Europe: Developing fire management in a dynamic landscape	Frontiers in Ecology and the Environment	Mod	Mod	Mod	Mod
Fischer, A.P.	2012	Identifying policy target groups with qualitative and quantitative methods: The case of wildfire risk on nonindustrial private forest lands	Forest Policy and Economics	Low-Mod	Low	Mod	Mod
Fleeger, W.E.	2008	Collaborating for success: Community Wildfire Protection Planning in the Arizona white mountains	Journal of Forestry	Low	Low	Mod	Low-Mod
Gan, J., Jarrett, A. and Johnson Gaither, C.	2015	Landowner response to wildfire risk: Adaptation, mitigation or doing nothing	Journal of Environmental Management 159 (2015) 186e191	Low-Mod	Low	Mod	Mod
Gazzard R, McMorrow J, Aylen J.	2016	Wildfire policy and management in England: an evolving response from Fire and Rescue Services, forestry and cross-sector groups.	Phil. Trans. R. Soc. B 371: 20150341	N/A	Mod	Mod-High	Mod
Glaves, D.J., Crowle, A.J.W., Bruemmer, C. and Lenaghan, S.A.	2020	The causes and prevention of wildfire on heathlands and peatlands in England. Natural England Evidence Review NEER014.	Natural England Report	Mod-High	High	High	Mod-High
Grant, A; Hooper, B; Langer, L	2017	Changing public behaviour: Enhanced and improved communication of fire behaviour	Fire and Emergency New Zealand Research Report Number 156	Mod-High	Moderate	High	Mod-High

Halliday L.G., Guy Castley J., Fitzsimons J.A., Tran C., Warnken J.	2012	Fire management on private conservation lands: Knowledge, perceptions and actions of landholders in eastern Australia	International Journal of Wildland Fire	Low-Mod	Low	Mod	Mod
Halliday L.G., Guy Castley J., Fitzsimons J.A., Tran C., Warnken J.	2012	Fire management on private conservation lands: Knowledge, perceptions and actions of landholders in eastern Australia	International Journal of Wildland Fire	Low-Mod	Low	Mod	Mod
Huffman, M.R.	2013	The many elements of traditional fire knowledge: synthesis, classification, and aids to cross-cultural problem solving in fire-dependent systems around the world.	Ecology and Society, 18(4).	Mod	Mod	Low	Mod
Jacobson, S.K., Monroe, M.C., Marynowski, S.	2001	Fire at the wildland interface: The influence of experience and mass media on public knowledge, attitudes, and behavioral intentions	Wildlife Society Bulletin	Low	Low	Low-Mod	Low-Mod
Jajtić, K., Galijan, V., Žafran, I., Cvitanović, M.	2019	Analysing wildfire occurrence through a mixed-method approach: A case study from the croatian mediterranean	Erdkunde	Low-Mod	Low	Mod	Low-Mod
Jakes, P.	2007	Social science informing forest management - Bringing new knowledge to fuels managers	Journal of Forestry	Low	Low	Low-Mod	Low-Mod
Jakes, P; Kelly, L; Langer, L	2010	An exploration of a fire-affected community undergoing change in New Zealand	Australian Journal of Emergency Management	Low-Mod	Low-Mod	Mod	Low-Mod
Jarrett, A., Gan, J., Johnson, C., Munn, I.A.	2009	Landowner awareness and adoption of wildfire programs in the southern United States	Journal of Forestry	Low	Low	Mod	Low-Mod
Jollands, M., Morris, J. and Moffat, A.J.	2011	Wildfires in Wales.	Forestry Commission Wales. Forest Research, Farnham	Mod-High	Moderate	High	Mod-High
Kouassi, J.-L., Wandan, N., Mbow, C.	2020	Exploring Wildfire Occurrence: Local Farmers' Perceptions and Adaptation Strategies in Central Côte d'Ivoire, West Africa	Journal of Sustainable Forestry	Low	Low	Mod	Mod
Langer, L and Wegner, S	2018	Wildfire risk awareness, perception and preparedness in the urban fringe in Aotearoa/New Zealand: Public responses to the 2017 Port Hills wildfire	Australasian Journal of Disaster and Trauma Studies	Low	Low-Mod	Low-Mod	Low-Mod
Langer, L; Hart, M	2014	Effective wildfire communication in New Zealand: Target the audience, tailor the message and tune the method	Scion and Bushfire CRC	Low-Mod	Low-Mod	Mod	Mod
Maguire, L.A., Albright, E.A.	2005	Can behavioral decision theory explain risk-averse fire management decisions?	Forest Ecology and Management	Low	Low-Mod	Mod	Mod
Martin, I.M., Martin, W.E., Raish, C.B.	2011	A qualitative and quantitative analysis of risk perception and treatment options as related to wildfires in the USDA FS region 3 national forests	USDA Forest Service - General Technical Report RMRS-GTR	Low	Low	Mod	Low

McCaffrey, S., Toman, E., Stidham, M., Shindler, B.	2015	Social Science Findings in the United States	Wildfire Hazards, Risks, and Disasters	Low	Low	Mod	Low-Mod
McMorrow J., Lindley S., Aylen J., Cavan G., Albertson K., & Boys D.	2009	Moorland Wildfire Risk, Visitors and Climate Change: Patterns, Prevention and Policy	in Bonn, A., Allott, T., Hubacek K. & Stewart J. (eds.) Drivers of Change in Upland Environments 404-431 (AUR)	Mod	Mod-High	Mod	Mod-High
Moffat, A.J. & Pearce, H. G.	2013	Contrasting approaches to forest fire risk in New Zealand and Great Britain	Scottish Forestry	Low-Mod	Low-Mod	Mod-High	Mod
Molina-Terrén, D.M., Cardil, A., & Kobziar, L.N.	2016	Practitioner perceptions of wildland fire management across South Europe and Latin America.	Forests, 7(9), 184	Low-Mod	Low-Mod	Mod	Low-Mod
Montiel, C and Kraus, D. (editors).	2010	Best Practices of Fire Use – Prescribed Burning and Suppression Fire Programmes in Selected Case-Study Regions in Europe.	Research Report 24. European Forest Institute.	Mod	Mod	Mod-High	Mod-High
Olsen C.S., Shindler B.A.	2010	Trust, acceptance, and citizenagency interactions after large fires: Influences on planning processes	International Journal of Wildland Fire	Low	Low	Mod	Low
Paveglio, T.B. Cassandra Moseley, Matthew S. Carroll, Daniel R. Williams, Emily Jane Davis, and A. Paige Fischer	2014	Categorizing the social context of the wildland urban interface: Adaptive capacity for wildfire and community "Archetypes"	Forest Science, 923 61(2), 298-310.¶	Low-Mod	Low	Mod	Low-Mod
Paveglio, T.B., Carroll, M.S., Stasiewicz, A.M., & Edgeley, C.M. (2019).	2019	Social fragmentation and wildfire management: Exploring the scale of adaptive action. Social fragmentation/values and wildfire management	Management, 71(74), 912 12-23.	Low-Mod	Low	Mod	Low-Mod
Paveglio, T.B., Stasiewicz, A.M., Edgeley, C.M.	2021	Understanding support for regulatory approaches to wildfire management and performance of property mitigations on private lands	Land Use Policy	Low	Low	Low-Mod	Low
Penman, T.D., Cirulis, B., Marcot, B.G.	2020	Bayesian decision network modeling for environmental risk management: A wildfire case study	Journal of Environmental Management	Low	Low	Mod	Low-Mod
Prior, T. and Eriksen, C.	2013	Wildfire preparedness, community cohesion and social–ecological systems	Global Environmental Change 23 (2013) 1575–1586	Low	Low	Mod	Low-Mod
Reed MS, Kenter JO, Hansda R, Martin J, Curtis T, Prior S, Hay M, Saxby H, Mills L, Post J, Garrod G, Proctor A, Collins O, Guy JA, Stewart G, Whittingham, M.	2020	Social barriers and opportunities to the implementation of the England Peatland Strategy	Natural England and Defra report	Mod	Mod-High	Mod-High	Mod-High

Remenick, L.	2018	The Role of Communication in Preparation for Wildland Fire: A Literature Review	Environmental Communication	Low	Low	Mod	Low-Mod
Ryan, R.L.	2012	The influence of landscape preference and environmental education on public attitudes toward wildfire management in the Northeast pine barrens (USA)	Landscape and Urban Planning	Low	Low	Mod	Low-Mod
Scion Rural Fire Reserach Update December 2011 Volume 10	2011	Communication of fire danger	Scion Rural Fire Reserach update December 2011	Mod	Low-Mod	Mod-High	Mod
Spies, T.A., White, E.M., Kline, J.D., Paige Fischer, A., Ager, A., Bailey, J., Bolte, J., Koch, J., Platt, E., Olsen, C.S., Jacobs, D., Shindler, B., Steen-Adams, M.M., Hammer, R.	2014	Examining fire-prone forest landscapes as coupled human and natural systems	Ecology and Society	Low-Mod	Low	Mod	Low-Mod
Stasiewicz, A.M., Paveglio, T.B.	2018	Wildfire Management Across Rangeland Ownerships: Factors Influencing Rangeland Fire Protection Association (RFPA) Establishment and Functioning	Rangeland Ecology and Management	Low-Mod	Low	Mod	Mod
Steelman, T.A., McCaffrey, S.M.	2011	What is limiting more flexible fire management-public or agency pressure?	Journal of Forestry	Low	Low	Low-Mod	Low
Steen-Adams, M.M., Charnley, S., Adams, M.D.	2017	Historical perspective on the influence of wildfire policy, law, and informal institutions on management and forest resilience in a multiownership, frequent-fire, coupled human and natural system in Oregon, USA	Ecology and Society	Low	Low	Mod	Low-Mod
Sturtevant, V., Moote, M.A., Jakes, P., & Cheng, A.S.	2005	Social science to improve fuels management: a synthesis of research on collaboration	Gen. Tech. Rep. Forest Service, North Central Research Station. 84 960 p., 257.	Low	Low	Mod	Low-Mod
Vadala, C.E., Bixler, R.D., Bransford, J.J., Waldrop, T.A.	2012	Attitudes, knowledge, and perception of fuel reduction among involved publics in the southern appalachians: Implications for responsive communication	Southern Journal of Applied Forestry	Low	Low	Mod	Low-Mod
Varela, E., Górriz-Mifsud, E., Ruiz-Mirazo, J., López-i-Gelats, F.	2018	Payment for targeted grazing: Integrating local shepherds into wildfire prevention	Forests	Low-Mod	Low	Mod	Mod