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Review Article

Navigating scientific uncertainty in wildfire and flood risk mitigation: A qualitative review

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ABSTRACT

Natural hazards are complex events whose mitigation has generated a diverse field of specialised natural science expertise that is drawn upon by a wide range of practitioners and decision-makers. In this paper, the authors bring natural science research, risk studies and science and technology studies together in aid of clarifying the role scientific uncertainties play in the mitigation of natural hazards and their associated risks. Given that uncertainty is a necessary part of scientific practise and method, those engaged in risk mitigation must manage these scientific uncertainties in their decision-making just as, equally, social science researchers, stakeholders and others hoping to understand risk mitigation must understand their character and influence. To this end, the authors present the results of an extensive literature review of scientific uncertainties as they emerge in relation to wildfire and flood risk mitigation in Australia. The results are both a survey of these major uncertainties and a novel categorisation within which a variety of expert and non-expert audiences might discuss and translate the scientific uncertainties that are encountered and managed in risk mitigation.

Contents

1. Introduction

Natural hazard risk mitigation is an exemplar of how, in today's world, we face complex challenges where uncertainty is rife. Natural hazards are complex events encompassing interconnected social, ecological, economic, and political dimensions that inform and influence each other through linear and non-linear feedback loops. Our attempts to manage natural hazards have generated a diverse field of specialised natural science expertise, providing profoundly useful and valuable insights, however uncertainty is also intrinsic to all scientific practises and methods; while further research may diminish some ambiguities, it also may leave others

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untouched, or introduce new uncertainties (see [126]). Individuals, practitioners and institutions engaged in risk mitigation necessarily encounter these scientific uncertainties in their decision-making, without the availability of straightforward solutions, and with the stressful prospects of both a natural hazard event, and the likelihood of having to account for decisions to official inquiries, courts, news media, and other forums.

In this paper, we bring natural science research, risk studies and science and technology studies together in aid of clarifying the role scientific uncertainties play in the mitigation of natural hazards and their associated risks. We do so with reference to two motivating concepts. The first is Ien Ang's notion of 'cultural intelligence': to take complexity seriously as an inherent and irreducible part of our world, whilst also finding conceptual and discursive ways to navigate through it [5]. The important work of simplification (not simplifying) to plot a course through complexity (rather than dispensing with it) is a strategic and enabling response to context. If social and physical science researchers do not diligently work to preserve complexity through simplification the former can, and very likely will, reappear when least welcome to render a schema null [97]. Similarly, while forms of scientific knowledge are crucial to understanding natural hazards, they are neither homogenous nor autonomous; it is not possible to simply defer to scientific authority to 'solve' the complex issues of reducing natural hazard risk, nor is it desirable to abandon the task of translating complexities across scientific and non-scientific contexts.

The second motivating concept is disaster risk reduction, or the identifying, assessing and reducing of disaster risks from a broad range of perspectives. Fostering the role of social resilience in reducing vulnerability is a vital aspect of risk reduction, an end that requires both increasing the range of available knowledge for problem-solving and building cross-scale problem-solving networks [12]. As such, resilience ideally involves the communication of scientific knowledge and its related uncertainties to non-expert groups. In regards to natural hazards, a significant amount of the attention paid to such communication has been within a 'hazard paradigm' (see [50]); that is, it has been focused on messaging, weighing the relative merits of incorporating uncertainty into the design and dissemination of scientific information (e.g. [73,14]). Rather than translating uncertainties 'out' to non-experts, an alternate approach towards resilience would be the production of 'dialogic' or 'middle' terms useful for participatory deliberation and the co-production of knowledge between expert and non-expert groups (see [36]).

As part of plotting the 'navigational' path, the authors have focused on two natural hazards in order to both review a broad selection of scientific methods and their uncertainties and to avoid compressing scientific complexities. Further, in order to maximise the practical applicability of this review we have focused upon uncertainties that emerge in wildfire and fluvial flood risk mitigation in Australia.[1] Australia is a land of marked seasonal variation, world renowned for 'droughts and flooding rains', as well as highly flammable eucalyptus forests. In January 2009, wildfires in Victoria led to 173 fatalities and the burning of 450,000 ha [34]. In December 2010–January 2011, floods in southeast Queensland were responsible for 37 fatalities, approximately $2.38 billion in damages, and an estimated $30 billion in lost revenue [128]. Though low frequency, these high magnitude hazard events have brought renewed public and government attention to their prediction and mitigation, particularly as their occurrence is likely to increase in Australia due to the effects of climate change [70]. Risk is also increasing due to demographic shifts into hazard areas such as floodplains and wildland–urban interfaces, and growing concern over biodiversity loss and rare and endangered species is bringing new dimensions to risk mitigation.

In the development of scientific knowledges around such floods and wildfires, and their application to risk mitigation, the challenges are multi-dimensional. For instance, not only are there issues relating to pure research and implementation—such as current knowledge, funding, institutional priorities, institutional literacy, intellectual property—but also the coordination of multiple scientific practises. Predicting and managing a hazard necessarily involves different methodologies, each attuned to different aspects of that hazard's probable occurrence and behaviour. For example, understanding flood risk in a given area typically involves not only climatological knowledge of the long-term trends in weather events, meteorological knowledge of short-term weather events, hydrological knowledge of rainfall-runoff responses and hydraulic knowledge of flow depth and velocity changes downstream; it also calls upon environmental–geographical knowledges regarding vegetation, topography, land use, population distribution and so on (see [29]). No one methodology can be relied upon to predict the probabilities and consequences of a given hazard, while together these diverse knowledges are more than the sum of their parts.

At the same time, the management of natural hazards in Australia, as in many countries, is conditioned also by institutional diversity. Different government and non-government agencies hold legal responsibility for different aspects of prevention, preparedness, response and recovery (the PPRR spectrum) in relation to different hazards. Historically, this distribution of responsibility has led to major operational issues and preventable losses during natural hazard events (e.g. [46,147]), leading to the recent 'all-hazards-all-agencies' policies [30]. The approach places a high value on technical interoperability between agencies, such as having compatible communication and information management systems and processes, and strategic interoperability, including sharing information, resources and planning exercises. As such, any one scientific methodology cannot and should not be considered the domain of any one individual or any one agency; optimally, knowledges and knowledge practises will pass through the necessary relays and translation between and within agencies efficiently. The assumption of the 'all-hazards' approach is that, as in the case of scientific methodologies more generally, together these diverse agencies are more than the sum of their parts.

Risk mitigation is also shaped by the intersecting public policy discourses of mutual responsibility and deliberative policy production (see [56,92,159]). In multiple ways, and with varying degrees of success, governments in Australia and elsewhere have made efforts to incorporate citizens into different aspects of policy planning and delivery, such as through greater public disclosure, incorporating stakeholders into design processes, conducting public education campaigns, amongst other strategies. The justification for such approaches may derive from normative values, such as democracy or equity, or functional values, such as efficiency and sustainability, and seek a variety of ends; as many commentators note, stakeholder engagement has sometimes been a method for responsibility-shifting by government agents and agencies [143]. Such considerations bring to the fore fundamental issues regarding the relative power and knowledges of those involved, particularly regarding knowledge diversity, public trust in scientific expertise and public understandings of science (see [132]). As the twinned sociological fields of risk studies and science and technology studies have made apparent, the boundaries between scientific research, scientific knowledges and the

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[1] For the sake of clarity, we focus on river (fluvial) floods (as against flash floods, urban floods, pluvial floods, sewer floods, coastal floods and glacial lake outburst floods) because they are the dominant hazard in Australia. A significant amount of the scientific practises presented here are nonetheless relevant to other forms of flooding.

political, economic and social context in which they are applied are 'permeable, changeable, and contestable' [144].

To be clear, the authors of this review neither subscribe to the 'deficit model' of the public understanding of science—which classes publics as knowledge-deficient and devalues the role of other knowledges in the co-production of scientific knowledge—nor do we contest the very idea of 'experts' [130]. There are significant and valid reasons to assume that expert scientific knowledges are different to others and that, therefore, the interface between diverse knowledges necessary to hazard prediction, 'all-hazards' management and deliberative policy is one of translation. Further, success in meeting these ends will hinge in part on the legibility of heterogeneous scientific methods to both risk practitioners operating in multiple institutional circumstances and non-experts. While Schaake et al. [121] state that there are 'tremendous uncertainties' in flood prediction, and Moore et al. [98] suggest that flood risk practitioners must 'embrace uncertainty', the authors of this review propose that such an embrace also requires practitioners and researchers to navigate and translate scientific uncertainties.

To this end, the authors completed a literature review of the diverse forms of scientific knowledge and uncertainties surrounding wildfire and flood risk. Using relevant databases (e.g. Web of Science, Scopus, Google Scholar), approximately 300 academic sources on wildfire and flood science were drawn upon in completing this review, including research on hazard modelling, prescribed burning, hydrological engineering, development planning, meteorology, climatology and evacuation planning. The review also incorporated indicative research regarding the public understandings of science, public policy, risk communication and deliberative planning in order to scope the significant uncertainties that emerge in risk mitigation practise. In reviewing this literature, though, the authors did not seek to itemise the uncertainties of each specific scientific practise, but rather to take a hazard-centred approach. This was done in order to focus on the uncertainties particular to these hazards while, at the same time, seeking to produce categories that are relevant to risk mitigation generally. The explicit aims of this review were therefore twofold. First, we sought to provide a comprehensive review of the scientific practises brought to bear in mitigating these two natural hazards. Second, in line with the aforementioned principles of fostering cultural intelligence and social resilience, we sought to develop a categorisation of uncertainties as they emerge in these practises that would be useful to discussions and translations within and between expert and non-expert audiences. As a result, the authors have identified three categories of uncertainty that are applicable across these hazards: historicist, instrumental, and interventionist. As both a description and a heuristic, this categorisation has been developed to provide greater clarity to researchers, practitioners, decision-makers and stakeholders working in this field.

2. Risk, risk mitigation and scientific uncertainty

Internationally, risk is typically considered as a function of a given hazard, the distribution of exposure to that hazard, and the vulnerability of what is exposed, measured in terms of consequences and probabilities (e.g. [69,71]). This complexity is widely articulated in the emergency management sector in Australia, for example, which identifies that wildfire risk arises out of the combination of the hazard (the wildfire prone landscape which is both physically and socially defined and created); what is considered at risk (usually, people, property, and ecological communities); and, the vulnerability or resilience of those considerations to the hazard (how they are affected by the hazard) (e.g. [47]). Often reduced to 'probability × consequences' [127], risk management in Australia emphasises the protection of people and property, with environmental values (e.g. flora and fauna) becoming increasingly recognised. The effect of wildfires, floods and other natural hazards are, in turn, often described in physical terms, though other impacts including emotional suffering for families and individuals, community distress, and reduced quality of life are also often considered [65].

While these various definitions are subtle and possess significant functional utility, they do not make explicit the situated and contingent character of probabilities and consequences, factors which can have a determining influence on policy and planning. As sociologist Peter Glasner [56] argues, 'any discussion of risk is as much about culture, institutions, perceptions, control and activity as it is about how risks are framed by experts'. As such, the sociological literature on risk has tended to speak of 'risk culture' or 'risk society'. A risk society, as described in the work of Ulrich Beck and Anthony Giddens, is a social formation in which vulnerability to, and responsibility for, hazards are the object of calculation and calculated distribution across populations. Reviewing this scholarship, Scott Lash [83] summarises its achievements as having uncovered the ways in which we are all articulated in relation to uncertainties and vulnerabilities—and practises of figuring uncertainties and vulnerabilities—that are neither simply individually chosen nor naturally allocated. As Beck argues [10], news media, scientific experts, governments, courts and insurance agencies, amongst others, are all important in shaping dominant definitions of what is and is not a risk, what causes a risk, who is liable for a risk, and so on.

Utilising geographer John Handmer's [58] tripartite analysis of flood risk, we can think of both wildfire and flood risk mitigation as an intermediary stage between 'risk creation' and 'residual risk'. Risk creation names those processes, such as urban planning, through which populations, values and assets are placed in relation to a natural hazard. Knowingly or unknowingly, consequences of various magnitudes are created in relation to hazard events of various probabilities. Subsequently, risk mitigation involves those processes through which government-mandated agencies and individuals attempt to limit given vulnerabilities to that hazard. Responsible agencies and people make choices regarding the relative importance of values and assets in light of the technical, political and economic feasibility of available mitigation strategies. Residual risk, in this schema, therefore names the processes through which remaining vulnerability is distributed to, and knowingly and unknowingly borne by, emergency management, private agencies and individuals, insurance companies and others. By design, such an analysis differs from broader definitions of risk management as 'the culture, processes and structures that are directed towards effective management of potential opportunities and adverse effects' [114]. The authors also note that the growing formal recognition of biodiversity and rare and endangered species as at-risk values during natural hazard events likely requires a modification of this tripartite analysis of risk to acknowledge that some values predate anthropogenic risk creation.

Like risk itself, the scientific knowledges utilised in mitigation are shaped—but not determined—by the context in which they emerge. This insight is at the centre of science and technology studies (STS), which emphasises the importance of examining how knowledges are produced and naturalised (see [55]). As sociologist David Turnbull [142] argues, we should think of scientific knowledges as sets of practises employed by specific individuals labouring in collaboration with specific apparatuses in specific institutional locations. For example, we calculate the likelihood and consequences of wildfire in a given place through an assemblage of agents: measuring devices (anemometers, thermometers, hygrometers, fuel estimation scales); archives of historical data (rainfall and burn history); and standardised algorithms produced through calibration and validation experiments to establish causal relations between multiple data and devices. Mitigation is, on this account, reliant on the creation of synthetic facts or 'combinable mobiles' [84], that are comprehensible, translatable and available across disparate locations. Through mitigation practises, scientific knowledges travel and are tested, becoming translocal and indeed transnational, whilst also always arising out of local practises and contexts (cf. [141]). Fire danger measures such as McArthur Forest Fire Danger Index (FFDI), the Canadian Forest Fire Weather Index System, and the United States National Fire Danger Ratings System are examples of such combinable mobiles, devised to represent hazard levels in a single quantum. Mitigation is also, therefore, both conventionalised and contingent in the sense that such devices, archives, algorithms and quanta are both functioning 'things-to-be-used' and fluid 'things-in-a-process-of-transformation' [78].

Unlike this review, which categorises uncertainties according to type, STS scholars have developed critical definitions of uncertainty according to levels of confidence. Wynne [158], for example, usefully differentiates risk, uncertainty, indeterminacy and ignorance (see also [131]). Whereas 'risk', in this instance, is the situation in which both parameters and probabilities are well known, in 'uncertainty' parameters are known but probabilities are not. Indeterminacy, alternately, points to the openness of causal chains, prone to interruptions, anomalies and human error. Such descriptive analyses of levels of uncertainty indicate that uncertainty itself is 'best seen as a relation… constructed from judgements based on possibly inadequate assumptions, and are therefore contingent' [126]. Further, this form of 'risk' is a misnomer for our purposes, in that it outlines a condition of perfect calculability that STS scholars, Wynne amongst them, deem an impossible and dangerous fantasy. Even if various parties implicitly or explicitly identify with such scientistic views, they do not reflect the realities of risk management and mitigation. In actuality, understanding natural hazard risk involves the epistemological wrangling of uncertainties around aleatory or chance events; the extent to which we can be confident in results are a matter of judgement about the parameters and probabilities at hand (see [138]).

Together, risk studies and STS illustrate the necessity of attending to how knowledge about a hazard is shaped by the contingencies of what may be, and what those involved contend may be, known and achieved in a place and time. In many instances, both lay and expert groups may only perceive a hazard 'downstream', long after its initial occurrence. In other instances, a form of risk mitigation based on available calculations may be mistaken for a surety, leading to drastic increases in the number of assets that are put at risk [25][123,129]. Thus, in thinking about risk mitigation we should not lose sight of the complex political, economic and social context in which the reception and utilisation of scientific research is a matter of 'who is engaged and which interests are represented' [107]. Just as scientific uncertainties can elicit necessary caution and new lines of inquiry, they can equally be exploited for partisan gain. This is clearly evident in the how uncertainties in climate change science have been used in public debate, media and politics [66].

None of this is to suggest that uncertainties surrounding natural hazards are necessarily overwhelming or that risk mitigation does not involve rigorous deliberative analysis. Instead, it raises two suppositions to frame further analysis. First, given that neither hazards nor at-risk values and assets are wholly calculable, the socioeconomic and socionatural effects of attempts to plan and understand mitigation interventions are also intrinsically uncertain. Just as uncertainties propagate across spatial levels of analysis, as in climate change scenarios (see [39]), so too do they accumulate across temporal levels of analysis. Future courses of action and inaction are not wholly knowable; uncertainty is a necessary condition of risk mitigation practise, though it is not necessarily a problematic condition. To use the 'Rumsfeldian' knowledge matrix, practitioners' levels of confidence operate within the shifting bounds of known knowns, known unknowns, unknown knowns and unknown unknowns [150]. Therefore, as Moore et al. [[98]] suggest in relation to flood risk, risk mitigation professionals must determinedly detect, analyse, manage and translate—or 'embrace'—uncertainty in their application of scientific knowledges if they hope to more comprehensively manage a given risk.

Second, risk mitigation policies and practises should be understood as historically conditioned, and not simply inevitable or optimal. This is a tenet often well understood by risk mitigation practitioners, attuned to the flaws of previous policies and practises, though nonetheless worth stating explicitly. In the United States, for example, the use of ignition suppression to mitigate wildfire risk [26,35] and the use of levees and other engineering solutions to mitigate flood risk [108,139] have proven flawed in their application, shaped as much by institutional 'lock-in', resource limitations and contemporary politics as by contemporary scientific knowledges. Today, in Australia, the dominant methods of wildfire risk mitigation are fuel reduction burning and other fuel treatments, development planning, building regulations and evacuation planning, while the dominant methods of flood risk mitigation are engineering works, development planning, building regulations and evacuation planning. It is important to remain aware that these forms of mitigation and their related uncertainties are not the only possibilities; they are simply the ones that hazard characteristics, landscape properties, and past and present events and trends have brought to prominence.

The following section reviews a significant body of contemporary scientific literature regarding wildfire and flood risk mitigation. For the purposes of this review, the authors have formulated three distinct categories of scientific uncertainties that are, to a greater or lesser extent, necessarily part of the scientific management of these hazards. In order to preserve complexity in these categories, each uncertainty is further subdivided into the two to three permutations or forms of uncertainty it comprises. These categories and forms are themselves a heuristic for further analysis and have been formulated to be comprehensive without being exhaustive. Examples of each form of uncertainty have been included in the hopes of also providing the reader with a sound survey of the dominant methodologies used by scientific practitioners in Australia to predict and mitigate these hazards.

3. Categories of scientific uncertainties

Following sociologists Collins and Evans [32], if we hope to understand scientific expertise and knowledges, we must pay attention to the extent to which their major debates and uncertainties are capable of relative 'closure' or consensus. In provocative (and perhaps unnecessarily normative) terms (see [115]), Collins and Evans usefully distinguish between 'normal science' fields, where core debates have been resolved within the scientific community, and three others. 'Golem science', the second category, names fields which contain the potential for such closure but have not yet reached a level of relative consensus.[2] Thus, whereas the medical use of vaccines would be an example of the 'normal' kind, an example of the latter would be the causal link between

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[2] Collins and Evans use of 'golem' corresponds to the creature from Jewish mythology.

Creutzfeldt–Jakob disease and BSE; such matters are 'golems' because their lack of relative closure gives them the potential for significant volatility. The last two categories outlined by Collins and Evans are related—'historical science' and 'reflexive historical science'—in that neither has significant potential to become 'normal', largely because they deal with unique historical trends rather than repeatable phenomena. Long-term weather forecasting and geology are examples of historical sciences, therefore, in that they are embedded in non-linear systems that cannot be replicated or modelled with 'normal' accuracy and certitude. Alternately, climate change is a *reflexive* historical question, in that actions informed by climate change science themselves may shape long-term climate phenomena.

3.1. *Historicist uncertainties*

Wildfire and flood risk mitigation are, as this section demonstrates, largely populated with (reflexive) historical sciences. As such, the first category of uncertainty stems from the necessary reliance of environmental sciences on historical data (see Table 1). That is, scientific methods devised to understand the behaviour of unique environmental systems are necessarily *historicist*, in that they assume a determining relation between the past, the present and the future [67]. Wildfire and flood behaviour models, for instance, are both validated by testing their ability to reproduce past hazard events from historical environmental inputs; in predicting floods, Lane et al. [82] write, 'the futures imagined [in modelling] are tied to pasts experienced' in data. Consequently, the first significant permutation of historicist uncertainties stem from the gaps and inconsistencies in available historical datasets on relevant environmental inputs, including gaps due to innovations in measuring apparatuses, variations in data metrics, and variations in the geographical spread of measuring apparatuses. For instance, the spatial and temporal

Table 1
Categories of scientific uncertainty in wildfire and flood risk mitigation.

Uncertainty type	Key question	Elaboration
Historicist: the uncertainties arising out of reliance on historical data, due to methodological relationships between the past, the present and the future	To what extent do gaps and inconsistencies in the datasets of relevant environmental variables affect confidence?	Gaps and inconsistencies can arise out of innovations in measuring apparatuses, variations in metrics, variations in the geographical spread of measuring apparatuses, unreliable apparatuses, the commercial sensitivity of some data, fragmented storage, funding constraints, and many other factors.
	Does the relative rarity, uniqueness and force of the given hazard event effect confidence?	A lack of historical exemplars is a barrier to prediction. For example: catchment data sets that are based on mean and medium river flow have limited insights into flood discharges; measuring apparatuses can be destroyed during wildfire and flood events; relative randomness of wildfire ignition points; and, fire behaviour unique to fire–terrain and fire–atmosphere interactions.
	To what extent do we assume that natural systems fluctuate within an envelope of stationarity?	Climate change requires recognition of both temporal and spatial variability into the future, the parameters of which are uncertain. Incorporating this 'new' variability can present significant obstacles.
Instrumental: the uncertainties arising out of limitations of a given apparatus, heuristic or theory[a]	To what extent are wildfire behaviours accounted for in algorithms and simulators?	Hazard behaviours are highly complex (e.g. feedback mechanisms between fire and atmosphere, the non-linearity of catchment responses to rainfall). Difficulties with capturing behaviours in models and algorithms may also stem from the limitations of computational resources, reporting requirements and historicist uncertainties, such as available data.
	What are the obstacles to assessing consequences to at-risk assets and values?	Assets and values may be spatially static (e.g. property, infrastructure) or spatially dynamic (e.g. human life, flora and fauna), which influences their incorporation into topographical modelling. Dynamic entities may be excluded or rendered through static proxies.
	To what extent are the relevant methodological standards contested?	Standards of analysis (e.g. FFDI, ARI) may be contested by researchers and others because they do not include all available data or relevant variables. These standards often inform the framing of scientific research.
Interventionist: the uncertainties arising out of calculating mitigation interventions and their effects	What are a baselines and metrics through which intervention effects have been quantified?	The calculation of the benefits and effects of mitigation interventions is subject to specific forms of historicist and instrumental uncertainty, particularly in regards to quantifying the benefit of interventions. What counts as 'risk'? Is additionally directly measureable?
	To what extent are we interrogating the parameters and primary, secondary and emergent consequences of interventions?	Are uncertain effects of interventions on at-risk values (e.g.: social effects such as 'safe development paradox' or 'levee effect', or the ecological effects of prescribed burning and dams and levees) considered? As Mitigation strategies and methods are influenced by non-scientific aspects such as policy priorities, social values, and political context, these unintended consequences should be considered calculable and non-calculable uncertainties.

[a] Note that wildfire risk is typically figured on likelihood of conducive conditions not on likelihood of occurrence. Flood risk is usually calculated in two ways: the likelihood of occurrence of rain-driven flood events; and, the spatial modelling of flood behaviour.

distribution of rainfall, land use, soil character (permeability, soil moisture content and its vertical distribution), ground water, channel characteristics, riverine vegetation and river management in floodplains all influence flood behaviour [76,80]. Rainfall is a highly localised phenomenon, though it is typically measured via point-based rain gauges whose placement is often highly inconsistent. Similarly, while the geographical extent of past wildfires is often available (or deducible), data on their intensity are relatively recent. There is also historic variation in wind speed metrics, meaning archives and practise are not only limited by unreliable measurements but also by the inhomogeneity of units of measurement and, thereby, data homogenisation processes [61,88]. In other instances, data are commercially sensitive or their collection and storage is fragmented across parties, creating further 'holes' in the datasets available to private and public agencies predicting and mitigating natural hazards. Such gaps and inconstancies in historical datasets are an irremediable limit that can have scientific and political consequences (e.g. [21]), though not necessarily significant ones.

A related second aspect of historicist uncertainty broadly applicable across environmental sciences stems from the relative rarity, uniqueness and force of a given hazard event. Cloke and Pappenberger [[29]] state that the rarity and extreme flow character of floods complicates flood prediction in three substantial ways. First, the bulk of historical data available on a catchment's behaviour can produce predictions of mean and median river flow, however these provide no major insights into flood discharges, which describe a nonlinear flow once they exceed the riverbank. Second, any attempt to evaluate meteorological forecasts for hydrological applications, and thus to validate flood forecasts, is fundamentally limited by the low frequency of extreme floods. It is difficult to test the correspondence between any hazard phenomenon and its projection in a given site without historical exemplars. Third, in cases where there are historical exemplars, rarity, force and uniqueness are still influential as measurements of river height, velocity or rate of rise may not be recorded or comprehensive, particularly as major flood events can sometimes exceed measuring devices and destroy measuring infrastructure. Equally, the rarity of wildfire events creates parallel uncertainties in wildfire prediction, not only because wildfire ignition points are relatively random, but also because wildfire behaviour is a product of unique fire–terrain and fire–atmosphere interactions (see [136,105,122]). The confidence of predictions is, in this sense, partly a product of the availability of well-described events for model validation.

The third permutation of historicist uncertainties stems from the common assumption in hazard prediction that natural systems fluctuate within an unchanging envelope of variability known as 'stationarity'. But, as Westra et al. [149] have argued, the scientific consensus regarding the existence of climate change puts in question both the parameters of this envelope and our ability to know this envelope, meaning that, as climate scientists suggest, 'stationarity is dead' [96].[3] Such dramatic proclamations do not, however, give any indication as to level of flux that must now be built into environmental sciences. That is, the extent to which climate change is relevant to the prediction of a given hazard varies widely depending on the temporal and spatial parameters of an analysis. For example, while a broad range of global climate models suggest that overall the Australian continent will 'experience consistent and extensive increases in fire probabilities' over the next 100 years [99], this increase may involve higher or lower rainfall or higher or lower fuel availability in different regions at different times [154,22]. The relevance of climate change to understandings of a hazard in a particular area is a product of the anticipated changes in given phenomena—rainfall, temperature, flora and fauna distribution, and so on—and the timespan over which they will occur (see [95,86,51]).

Overall, historicist uncertainties emerge from the reliance of scientific knowledges on archives of historical data. Their relevance in any one context varies. To the extent that they are able to draw upon rich datasets and well-described historical exemplar events, and incorporate relevant climate change scenarios, scientific knowledges are minimally limited by historicist uncertainties.

3.2. Instrumental uncertainties

The instruments brought to bear by scientific practitioners to synthesise such heterogeneous data incorporate their own uncertainties, and while these are particular to each individual context they can nonetheless be broadly categorised. Instrumental uncertainties emerge from the limitations of a given apparatus, heuristic or theory used to calculate the probability and consequences of hazard events. As such, it is first worth delineating the dominant ways in which risk calculations occur. For example, wildfire risk in Australia is typically figured in terms of the likelihood of conditions conducive to wildfire and not the likelihood of occurrence (or ignition). Temperature, relative humidity, wind speed and an estimate of fuel conditions are synthesised as an FFDI number predicting the intensity of a hypothetical fire (see [88]), meaning short-term and long-term forecasts of such spatial data can be used to forecast 'fire weather' (e.g. [59]). As in other fire-prone countries, the companions to such an instrument are wildfire simulators [103], capable of combining fire spread algorithms with spatial data to simulate a wildfire's behaviour within a landscape (regarding simulators see [72,135]). Similarly, flood risk is typically calculated in two ways, the first being the likelihood of occurrence of rainfall-driven flood events, produced from statistical analyses of meteorological and archaeological evidence of past flood events (see [77,11]). The second aspect is a 'flood study', which combines hydrological and hydraulic flood behaviour algorithms with spatial data to simulate flood behaviour within a floodplain ([147], regarding simulators see [68]). In each case, as in meteorological Numerical Weather Prediction (NWP) systems, wildfire and flood hazard 'calculation systems' often incorporate Monte Carlo ensemble prediction techniques—where the probabilities of variations around a central 'control' forecast are tested through multiple scenarios—to make forecast uncertainty legible (e.g. [79,29,48,43]).

In surveying these likelihood and consequence techniques it is clear that there are three significant versions of instrumental uncertainty. The first stems from the difficulty of capturing hazard behaviours in simulators, specifically due to uncertainties surrounding behaviour algorithms. As engineer Richard Rothermel [117] noted, it is quite unlikely that the minute-by-minute movement of a fire will ever be accurately predictable due to factors such as the erratic nature of surface winds and fuel heterogeneity [134,62]. Nonetheless, wildfire models anticipate the macro-dynamics of wildfire through algorithms representing surface fire spread, crown fire spread, spot fire spread and atmosphere interaction [103]. The algorithms used within a simulator may be theoretical, semi-empirical and/or empirical in any given instance, each with their own benefits and limitations. Some behaviours, such as the distribution of firebrands by ambient winds or convection columns (known as 'spotting'), are more elusive than others [103]. As Saeedian et al. [118] suggest, spotting is difficult because it incorporates eight elusive variables and is dramatically influenced by wind dynamics. Feedback mechanisms between fire and atmosphere can also be difficult to model [100,136]. The

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[3] El Niño Southern Oscillation (ENSO) and other similar global fluctuations also challenge the precept of stationarity.

micro-dynamics of floods are no less mysterious, particularly in regards to surface and subsurface flow processes and the influence of flow resistance (see [89]). Whereas the physics of hydrology and hydraulics assume conservation of mass and momentum, catchment responses to rainfall are necessarily non-linear, meaning outputs are not directly proportional to inputs [79].

It is important to note two distinct but associated issues faced by those simulating hazard behaviours. The first, linked to historicist uncertainty, is the possible paucity of relevant spatial data due to resource constraints. While it is widely acknowledged that data collection is a costly and difficult business, it is important to understand the influence of available data infrastructure on a system. For example, several recent government inquiries in Australia have concluded that the coverage of rain and stream gauges across catchments in Australia is highly inconsistent—due primarily to funding shortfalls and inter-jurisdictional debates [112,147]—which in turn has consequences for flood mapping [9]. Second, like all scientific practise, risk mitigation is limited by what historian Paul Edwards [45] calls the 'data and computational friction' of modelling. In practise, any synthesis of data to calculate probabilities and generate scenarios strains against the limitations of available computational resources and reporting requirements (e.g. [20]). Thus, uncertainties may be introduced to the practical work of risk mitigation to manage computational drag. Measuring apparatuses and resources are finite and we come to 'know' the behaviour of a system within institutional bounds whose finitude and influence may themselves not be obvious (e.g. [110,37]).

If the first form of instrumental uncertainty centres on the rendering of hazard behaviours, the second iteration centres on the modelling of at-risk assets and values. What counts as an asset or value varies, though human life and property are almost universally prioritised, ahead of critical infrastructure and rare and endangered flora and fauna. Broadly, we can divide these assets and values between spatially static entities (property, infrastructure) and spatially dynamic entities (human life, flora and fauna) as different kinds of challenges. Static entities can be reasonably easily incorporated into such topographical modelling, for example as points indicating property position and elevation. A modelled wildfire can, thereby, be used to estimate risk to property by relating radiant heat to property loss ([140,31], regarding property loss in floods see [6,44]). Data on infrastructure position and elevation can similarly be incorporated into hydraulic flood models (e.g. [60]). Alternately, spatially dynamic entities are somewhat more problematic and, as such, are either excluded or, more typically, rendered through static proxies. For example, given the difficulty of predicting human behaviour, users of ensemble wildfire modelling software programme PHOENIX RapidFire use property data as a proxy for human life [2]. In other instances, risk modellers are able to borrow the synthetic proxies that ecologists have developed to measure dynamic entities such as flora and fauna as biodiversity metrics (e.g. [153,91,75]). While there are important caveats regarding the correspondence between such measures and actual populations, to the extent that such calculable proxies can be assigned to spatial units—and relation between hazard behaviours and consequences are known (e.g. [17])—such assets and values are able to be integrated into models. In general, significant uncertainties surround both the prediction and quantification of dynamic entities. Just as it is notoriously difficult to predict human behaviours in relation to hazard warnings and hazard events (e.g. [152,49,74,106,93]), it is, for different reasons, very difficult to quantify the relation between biodiversity and wildfire events (e.g. [4,155]).

The third iteration of instrumental uncertainty stems from the adoption of methodologies and methodological standards whose applicability and accuracy are contested, yet continue to iteratively influence the framing of scientific methods and projects. Related to the uncertainties sourced in data collection, these uncertainties may originate in resource limitations or 'cultural' factors such as institutional preferences and literacies, also known as path dependency (see [156,13]). Wildfire and flood risk mitigation in Australia both offer primary examples of these standards. Across Australia, as in Europe [36], most jurisdictions use a '100-year flood' event as the general standard in flood modelling, mapping and development planning [33]. This standard has different names —1% AEP (Annual Exceedence Probability), 100ARI (Average Recurrence Interval), Q100—but, as Wenger et al. [147] explain, it is always 'a statistical estimate of the average period in years between the occurrence of a flood of a given size'; a 1% AEP or 100ARI flood event have a 1:100 likelihood of occurring in any given year. But to speak of averages is to invoke a historical dataset and, thereby, the contention that the given system is sufficiently documented and sufficiently stationary as to be averaged. Specifically, this standard has been criticised for being 'a very coarse tool' for judging and communicating flood risk [157,63], particularly in floodplains where there is a considerable difference between a 1%AEP and Probable Maximum Flood (PMF)—the theoretically largest flood that could conceivably occur. In such cases, the standard measure is arguably biased towards underestimating risk [124,15]. While currently the dataset that forms the basis of flood estimation is being thoroughly revised in Australia (see [8]), as it was last updated in 1987, it is worth noting that standard flood forecasting approaches in the U.S. and United Kingdom have also recently undergone major criticism [146,148].

Like 1% AEP, the standard measure of wildfire hazard in Australia is a tool of translation based upon historical data; FFDI, developed in the 1960s by McArthur and others (see [111]), uses the conditions on 13 January 1939 or 'Black Friday' in Victoria to represent the (former) maximum of 100 FFDI [3]. While many consider its simplicity and translatability to be real benefits [119], others have drawn attention to its insensitivity to ecological variation, its high sensitivity to input variation under extreme conditions, and its inability to incorporate several significant environmental factors that influence fire behaviour such as fuel type and topology (e.g. [133,40]). Nonetheless, the institutionalisation of FFDI as the standard measure of hazard means that it is not only central to risk mitigation, but also public understandings of fire risk and the dangers of climate change (e.g. [64]). Like 1% AEP, this scientific standard has an operational utility which may inadvertently mask the uncertainties and suppositions underpinning it. In sum, instrumental uncertainties emerge from the internal and practical limitations of a given apparatus or algorithm. That is, to the extent that hazard behaviours can be articulated from available algorithms and spatial data, at-risk values and assets can be incorporated into hazard simulations, and methodological standards are current and revisable, scientific knowledges are minimally limited by instrumental uncertainties.

3.3. *Interventionist uncertainties*

The final category of scientific uncertainty addressed by this review is interventionist uncertainties, which emerge from predictive calculations regarding the effect of a mitigation intervention. Such interventions may include legal reforms, policy changes, strategic planning and engineering works, amongst others. Each of these nominates a broad spectrum of strategies to manage a risk, often by geographically and/or temporally redistributing it. For instance, remediation of flood hazard through engineering includes dams, levees, detention basins (or 'dry dams'), flood walls, land clearance, dredging, backflow prevention and evacuation infrastructure (see [147]). Wildfire-related engineering works include fuel breaks, fuel reduction burning, slashing and thinning

[53]. In order to address the spectrum of such interventions, we restrict ourselves to the two primary permutations of interventionist uncertainties. The first stems from the common challenge of quantifying intervention additionality. Interventions are typically justified through their anticipated social, environmental or economic benefit, however this benefit is rife with uncertainties. Looking at the example of prescribed burning, the dominant form of wildfire risk mitigation in Australia, decades of experimental data have validated the correlation between increases in the average area burnt for fuel reduction and decreases in the average area burnt by wildfires [125,19]. However, this correlation tells us little about how these burns spatially redistribute risk. While one policy response since the early 2000s has been to intensively reduce fuels surrounding suburbs and towns [52], state agencies have also begun to use ensemble simulators to test treatment scenarios across landscapes. In Victoria, state agencies simulate wildfires under extreme conditions over a control scenario (no fuel reduction or fire history) and an experimental scenario (with fuel reduction and fire history), measuring risk in terms of the difference between predicted property losses [38]. Subtle and innovative as this strategy is, it demonstrates the dependence of additionality on the parameters of analysis: the description in spatial data of the present environment; the design of a control scenario; the selection of a hazard event; and, the selection of a metric of benefit. The same is true, for instance, in modelling the additionality of raising a dam wall (e.g. [60,41]). Is the control scenario credible? Is the hazard event sufficiently or excessively cautious? Is a metric, such as economic benefit, discretely calculable? As such, interventions import historicist and instrumental uncertainties of their own and are very clearly influenced by non-scientific aspects of mitigation such as policy priorities, worldviews, institutional path dependencies and other contextual influences.

If the first uncertainty relates to the demonstration of intervention efficacy, the second relates to its reflexivity. As noted earlier, confidence in mitigations can lead to unintended consequences such as the 'safe development paradox', or what geographer Gilbert White [151] described as the 'levee effect' (see also [108,123][104, 7],: 232–234,[25]). Governments, developers and others may mistake engineering works for protection, subsequently reducing development controls and placing more development in a perceived 'safe' area. Residents, often unknowingly, then bare high levels of residual risk. Similarly, researchers have suggested that the perceived effectiveness of risk mitigation amongst residents can lead to lower levels of preparedness (e.g. [1,24,57]). Arguably, to return to Wynne's typology, these are situations of 'indeterminacy' produced by unintended social consequences beyond the control or consideration of scientific methods. However, where a correlation is or may be established they would perhaps be better understood as calculable or non-calculable uncertainties. Looking at evacuation planning, for example, some modellers have attempted to take into consideration the probabilities of delays that often occur within evacuations, such as response lag and traffic accidents, in order to calculate the previously indeterminate (e.g. [102,109]). Other consequences, such as the ecological consequences of levees and dams to soil erosion and flood dependant species, are only apparent 'downstream' after an intervention ([147], for examples see [116,101]). Today, as Clode and Elgar [28], there are significant concerns about the health, safety, and ecological impact of broad-scale prescribed burning (see also [27]). For example, in some instances effects on insect life [137] and biodiversity [23,27,42] may only become included in mitigation analyses after implementation.

Alternately, the efficacy of forms of mitigation based around development planning and building design may or may not include considerations of implementation. So while the additionality of planning interventions can be quantified 'upstream', as Godden and Kung [54], this may require ignoring the frequency with which such regulations may be waived or not applied (see [90]). Similar considerations emerge regarding the application of scientifically-tested regulations stipulating the use of flood and/or fire resistant building materials and design (e.g. [113,85,94]). In short, every mitigation strategy elicits a set of uncertainties relating to its ability to calculate and incorporate consequences of different types, including secondary and unforeseen consequences. 'Embracing uncertainty', therefore, must also include consideration by risk mitigation practitioners of the relative ability and legal capability of relevant agencies and individuals to be reflexive in regards to the parameters and consequences of interventions. To the extent that the additionality of a given intervention can be quantified with a high degree of confidence, and primary, secondary and emergent consequences can be calculated (and are), scientific knowledges are minimally limited by interventionist uncertainties.

4. Discussion and conclusion

While a test of these categories is beyond the scope of this review, it is worth reflecting on how these categories might be utilised in discussing the science of wildfire and flood risk mitigation. Taking the example of wildfire, utilising these categories would necessarily require an empirical rather than ideal approach in a given circumstance. This would proceed by first attending to *historicist* foundations of risk calculation, meaning the actual data used for estimating risk, asking: to what extent do gaps and inconsistencies in the datasets of relevant environmental variables affect confidence? To what extent does the relative rarity, uniqueness and force of a wildfire event affect confidence? To what extent do we assume that natural systems fluctuate within an envelope of stationarity? Second, the *instrumental* methods actually being used to calculate risk would need to be discussed, including: to what extent are wildfire behaviours accounted for in algorithms and simulators? What are the obstacles to assessing consequences to at-risk assets and values? To what extent are the relevant methodological standards contested? Third, the measurement of *interventionist* strategies used and contemplated would be analysed, including: what are a baselines and metrics through which intervention effects have been quantified? To what extent are we interrogating the parameters and primary, secondary and emergent consequences of interventions? Focusing on *forms* of uncertainty in this way differs substantially from a focus on descriptions of overall scientific confidence, as adopted by the IPCC and many others. That is, rather than give a synthetic description of the overall state of scientific knowledge, these qualitative considerations point towards a deliberative analysis of applied knowledge. As such, the categories developed here are less a 'risk instrument' for transferring information than a programme for 'risk dialogue' between expert and non-expert groups about how risk is (and can be) quantified and how it is (and can be) mitigated.

Scientific uncertainty can be an inflammatory topic in discussions of natural sciences and environmental interventions, as there are many historical instances in which a lack of certainty has been exploited to defer responsibility and delay action on urgent issues. As Sarewitz [120] argues, such manipulation of uncertainty hinges on an inherently flawed understanding of the relation between science, uncertainty and effective action. In short, because there are thresholds to the relative certainty and relevance of data, more data does not necessarily create more certainty just as more certainty does not necessarily elicit more effective action. Similarly, this review has shown that not all uncertainties are created equal in their influence or responsiveness to research. A related concern for practitioners has been how scientific uncertainties should be effectively communicated outside specialist circles, given both the dangers of distortion and the benefits of increased public understanding of science. There is, for instance, a growing literature on the relative effectiveness of different expressions of scientific confidence—such as natural frequency, odds ratios, mortality rates, survival rates—on promoting understanding or action in target groups [145]. More broadly, there are significant sociological and philosophical debates about the social effects and normative merits of communicating uncertainties to non-scientific audiences (see [49]). These debates relate to even larger questions about the merits, modes and possible limits of transparency in the relay of scientific knowledges between scientific experts, government agencies, private companies and publics. The fact that uncertainties are necessary variables in the production of all scientific knowledges means that the communication of uncertainties is necessarily a matter of interest to the people creating the knowledge and the people for whom it is intended.

The detection and analysis of scientific uncertainties relating to wildfire and flood risk mitigation serve a variety of potential purposes for different audiences. First, for scientific researchers in these fields, attention to the present limits of certainty are a necessary and productive element in the design, execution and reporting of scientific results. The present mapping of relatively uncertain relations is, as Landström and Whatmore [81] point out, a significant factor in environmental researchers' own subsequent decisions about the selection and funding of future projects. Second, for risk mitigation professionals, the present limits of certainty are not only relevant to decision-making processes regarding the prediction and mitigation of a hazard, but also the justification of decisions, the identification of knowledge deficits and the advocacy of policy changes to publics, courts, researchers and policymakers, amongst others. Third, there are significant but different potential benefits to both publics and policymakers in acquiring a more robust understanding of scientific uncertainties. For publics, this has the potential to create greater participation in, and ownership of, policy priorities and decisions as well as, some sociologists suggest, greater personal responsibility for managing residual risk (e.g. [87,16]). For policymakers, while uncertainty has frequently been a source of delay and deferral, it is also possible that an enhanced understanding of uncertainties could significantly inform precautionary planning decisions in regards to at-risk areas (see [18]). The authors suggest that given both the need for communication about scientific uncertainties between different parties, and the potential benefits of increased understanding of these uncertainties, the categories outlined in this literature review will prove useful tools of translation for diverse groups. Researchers, stakeholders and policy-makers hoping to understand the scientific basis of risk mitigation policy and practise must consider the extent to which different risk mitigation options are shaped by historicist, instrumental and interventionist uncertainties. Finally, the authors contend that the categories of uncertainty established through this review will prove useful as tools of analysis and translation to social science researchers engaging with professionals in natural hazard mitigation and modelling. Like risk mitigation professionals themselves, social science researchers must use their knowledge of knowledge and uncertainty as part of the analytical tools needed to navigate through contextual complexity [5]. This review has provided one such tool to this growing area of research.

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