We describe a new framework for quantitative bushfire risk assessment that has been produced by Geoscience Australia as a part of the Bushfire Cooperative Research Centre’s (Bushfire CRC) research program. The framework builds upon the well-defined processes in the Australian Risk Management standard (AS/NZS ISO 31000:2009) and the National Emergency Risk Assessment Guidelines. It is aimed at assisting state-of-the-art fire research in Australia, and fire risk managers in state and territory governments, by (a) defining the essential elements for calculating bushfire risk, (b) providing a reference on how to undertake a computational bushfire risk assessment and, (c) indirectly, improving the quality and consistency of information on bushfire risk in Australia. There is a need for improved risk information to address the recommendations on bushfire risk management from the inquiries held after disastrous fires in Australia in the past decade. Quantitative techniques will improve this risk information. However, quantitative bushfire risk assessment is in its infancy in Australia. We use the example of calculating house damage and loss to demonstrate the elements of the framework.

Introduction

Bushfire is one of the most frequent natural hazards affecting Australia (Bradstock et al. 2012). It has shaped the Australian landscape and ecology and is an intrinsic part of the natural system of this continent. Yet, in extreme cases, bushfires are devastating events that cause injuries and fatalities and destroy property and communities. Although hundreds of fires burn every year in Australia, very few of these cause significant damage. Since 1939, six events in Australia account for more than 60 per cent of all house loss from fire, and house loss is almost always associated with extreme fire weather (Blanchi et al. 2010). For example, the 7 February 2009 Black Saturday fires in Victoria resulted in 173 fatalities and direct economic costs conservatively estimated at $4.4 billion (2009 Victorian Bushfires Royal Commission (VBRC), 2010a). The Ash Wednesday fires in Victoria and South Australia in 1983 caused 75 fatalities and over 2800 buildings were destroyed (VBRC 2010b, 2010c).

There is an increased demand for improved risk information on bushfires and improved techniques to provide this information as an outcome of the impacts of extreme fires in Australia in the past decade. The demand is driven in part by relevant recommendations from the VBRC (2010d) and the 2005 report to the Council of Australian Governments on bushfires (Department of Transport and Regional Services, 2005).

Fire risk is often used interchangeably with fire danger, for example as quantified by the McArthur fire danger indices for forest and grassland. However, fire risk represents a wider perspective than fire danger, as it considers the probability of fire, for example through fuel availability and chance of ignition, as well as the potential impacts that vary with the presence of assets that can be damaged, and their particular vulnerability to fire. Fire danger rating classes are designed for public warnings, bans and permits, and suppression preparedness, which often vary on a daily basis. Understanding and quantifying fire risk is usually undertaken to support development of risk management strategies, mostly from a longer-term perspective.

This paper gives an overview of the newly-developed ‘Quantitative Bushfire Risk Assessment Framework for Severe and Extreme Fires’ (Jones et al. 2012). The framework has been developed to address the above mentioned demand and it focuses on extreme fires and their impact on the human environment. The framework is utilised by the Bushfire Cooperative Research Centre (Bushfire CRC) risk research program. The Bushfire CRC’s FIRE-DST project (Fire Impact and Risk Evaluation – Decision Support Tool) is currently developing a quantitative computational tool that can assess the direct impact of potential bushfire events on rural and peri-urban communities, both responding to an immediate threat and also examining possible extreme
scenarios that may pose a threat at a future point in time. The development of FIRE-DST involves a collaborative effort between Geoscience Australia, Melbourne University, the Bureau of Meteorology and two divisions of the CSIRO. FIRE-DST is aimed at enabling fire and land management authorities to use evidence-based decisions to develop appropriate fire impact and risk treatment options. This framework is therefore aimed at researchers and fire and planning agencies in State and Territory governments.

The aims of the framework are:
• to define the essential elements for calculating bushfire impacts and risks in Australia;
• to provide a reference on how to undertake a computational bushfire impact assessment or risk assessment, drawing on other standards and guidelines (although the framework is not a guideline itself); and
• indirectly, by application of this framework, to improve the quality, consistency and availability of information on bushfire impacts and risks in Australia.

Risk and risk assessment

Risk can be defined as ‘the combination of the probability of an event and its negative consequences’ (UNISDR 2011). Risk assessment is an essential step in a risk management procedure. Risk assessment is the determination of quantitative or qualitative value of risk related to a plausible situation and a recognized threat or hazard. Quantitative risk assessment requires calculations of two components of risk; the magnitude of the potential loss, and the probability that the loss will occur. Risk assessments are routinely performed for many applications, for example in financial, aerospace, military, nuclear power and medical industries. Methods for assessment of risk may differ between industries and whether it pertains to general financial decisions or environmental, ecological, or public health risk assessment.

Computational bushfire risk assessment is in an early stage of development in Australia, and practitioners currently use largely qualitative methods with differing terminologies and approaches to assess bushfire risk. A discussion of previous bushfire risk studies can be found in Atkinson et al. (2010) which also includes a discussion of quantitative and statistical approaches.

This overarching framework provides a reference for consistent use of terminology and allows users to determine if in fact they are undertaking a risk assessment or something different. The outcomes can improve confidence in bushfire risk assessment results and the ability of risk managers, policy makers and others to compare results between studies.

The framework is built upon the Australian/New Zealand standard for risk management AS/NZS ISO 31009:2009 (Standards Australia and Standards New Zealand 2009) and the National Emergency Risk Assessment Guidelines (National Emergency Management Committee (NEMC) 2010).

Fig. 1. Schematic of the Quantitative Bushfire Risk Assessment Framework. The specific components and pathways addressed by the Bushfire CRC’s FIRE-DST project are emphasised in bold lines (www.bushfirecrc.com).
Quantitative framework elements and functions

The quantitative risk assessment approach described in this paper breaks the risk analysis process down into elements that can be modelled computationally. The elements considered are hazard, exposure, vulnerability, impact and risk. A schematic diagram of the framework is shown in Fig. 1. As a simple example, hazard can be quantified as the intensity of radiant heat caused by the fire, while the exposure specifies which assets, for example buildings, are exposed to the fire. The vulnerability element describes how susceptible each building is to damage given the intensity of radiant heat it experiences. The impact (or consequence) of an event is specified as a function of hazard, exposure and vulnerability, i.e.:

\[
\text{Impact} = f(\text{hazard, exposure, vulnerability}) \quad \ldots(1)
\]

Impact is quantified in terms of the damage to exposure, for example repair or replacement costs of the damaged buildings. Risk is the likelihood of damage to the buildings from the bushfire, integrated across the entire spectrum of possible events:

\[
\text{Risk} = f(\text{impact, likelihood}) \quad \ldots(2)
\]

In the framework diagram in Fig. 1, users choose the pathways (dashed lines) from left (hazard) to right (risk) that lead them through the framework elements to the selected impacts or risks of interest. This paper uses house damage as an example and works through the elements of the framework pointing out some key steps in analysing impact and risk. House damage can form a significant part of the framework pointing out some key steps in analysing impact and risk. House damage can form a significant part of the framework pointing out some key steps in analysing impact and risk. House damage can form a significant part of the framework pointing out some key steps in analysing impact and risk. House damage can form a significant part of the framework pointing out some key steps in analysing impact and risk. House damage can form a significant part of the framework pointing out some key steps in analysing impact and risk. House damage can form a significant part of the framework pointing out some key steps in analysing impact and risk. House damage can form a significant part of the framework pointing out some key steps in analysing impact and risk. House damage can form a significant part of the framework pointing out some key steps in analysing impact and risk. House damage can form a significant part of the framework pointing out some key steps in analysing impact and risk. House damage can form a significant part of the framework pointing out some key steps in analysing impact and risk. House damage can form a significant part of the framework pointing out some key steps in analysing impact and risk.

Hazard

Hazard can be defined as ‘a source of potential harm’ (National Emergency Management Committee 2010). ‘Hazard’ is the first element in the framework. A hazard ‘footprint’ describes the maximum intensity of a bushfire event across its spatial extent. The Hazard element in the framework includes many essential processes, models and key datasets for bushfire risk assessment. These include models for extreme fire weather, ignition likelihood and fire-spread and datasets for fuel loads, moisture content, vegetation and elevation.

There are four mechanisms included in the framework by which bushfires attack buildings and people:
- ember contact;
- radiant heat including direct flame contact;
- severe winds; and
- smoke.

Whilst physical evidence from historical fires in Australia indicates that ember attack is the major cause of house loss (Blanchi and Leonard 2005), the predominant reason for fatalities during bushfires is exposure to radiant heat and flames. Where houses are partially burned, smoke can cause significant damage to interior surfaces, fittings and contents. Severe wind associated with either the fire event (e.g. convective gusts) or the broadscale meteorology can weaken the structure and make it more vulnerable to ember attack. For example, shattering of roof tiles by strong winds can enable embers to penetrate into a roof cavity. Quantifying the hazard by estimating the intensity of each attack mechanism translates the output of the hazard element into the next elements of the framework.

Fire suppression

Fire suppression can be defined as ‘the activities connected with restricting the spread of a fire following its detection and before making it safe’ (AFAC 2011). Fire is different from other natural hazards in that human intervention can alter the fire hazard during the event. Furthermore, the fuel hazard can be mitigated prior to a bushfire event by the control of specific fuel loads. Suppression techniques can be implicitly subsumed in the hazard or vulnerability models. However, including it explicitly in the framework
allows users of the framework to quantify the effectiveness of alternative suppression techniques and operations.

Fire suppression is costly and cost models for fire suppression are important in making accurate estimates of fire impact and risk. The cost of supplementary suppression funding for fighting the 2009 Victorian fires was estimated at about $593 million or about fourteen percent of the total costs of the fires (VBRC 2010a). The total cost of fire suppression in Victoria in 2008–09 was estimated to be approximately $1439 million (Victorian Department of Treasury and Finance 2009).

Exposure
Exposure can be defined as ‘people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses’ (UNISDR 2011). Many schemes for exposure are used in Australian jurisdictions. We mention two different schemes that are appropriate for use in the framework.

The Australian Natural Disaster Impacts Framework Project has defined a list of community attributes at risk to bushfires (Stephenson 2010). The project’s definitions of ‘objects’ cover social, economic and environmental considerations. We use these categories for exposure in the schematic diagram of the framework (Fig. 1).

The National Exposure Information System (NEXIS) is a powerful, nationally consistent exposure dataset with information on buildings, contents and residents. Geoscience Australia is the developer and custodian of the database (Nadimpalli et al. 2007). NEXIS contains detailed information for:
- residential exposure (location, type, size and value of structures) and residents (numbers and average income); and
- commercial and industrial exposure (location, construction materials, replacement values, business types, employees, customers and turnover).

Vulnerability
Vulnerability can be defined as ‘the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard’ (UNISDR 2011). We discuss vulnerability modelling for housing in the framework and in this paper as an example, though the approach is generic and applies to other exposures. A first stage in vulnerability modelling is the preparation of fragility curves where the damage to a house can be determined by the magnitude of the hazard variable, for example, the intensity of radiation that will cause a wooden door or window to ignite, or the strength of a gust of wind that damages an unsecured tiled roof. Figure 2 shows examples of fragility curves for house damage. The fragility curves specify the expected percentage of houses suffering total damage from ember attack within a population of a generic house type. Other fragility curves could be plotted showing the percentage of houses in partial damage states (HAZUS 2003).

A next stage in vulnerability modelling is the preparation of damage curves. An example is shown in Fig. 3 for wind damage. In the 2009 Victorian fires building impact assessment thirteen per cent of the surveyed houses (135 houses) had wind identified as a mechanism that compromised the structure, as well as fire (Leonard et al. 2009). The damage index is the reinstatement or repair cost of the exposed population of houses divided by their total replacement value. A damage index equal to 1.0 means that all buildings have suffered a damage loss equivalent to 100 per cent of the replacement costs. A cost model is required.

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Fig. 2. Fragility curves for total building loss due to ember attack on a generic house design (unpublished and preliminary data; FIRE-DST project December 2011). The difference between the curves illustrates that the percentage of house loss caused by ember attack varies with fuel moisture content.

Fig. 3. Example wind damage curve for housing (Geoscience Australia). The curve relates the building structural damage to the wind gust speed at 10 m height.
to produce damage curves. The cost model translates direct damage into impact in terms of dollar values. Cost models for buildings and contents can be prepared with the aid of quantity surveyors, engineers, insurance companies and demographers (HAZUS 2003).

FIRE-DST employs a probabilistic logic tree or event tree approach that computes the conditional likelihood of damage from the many possible ways that a fire can attack exposed assets. The branches of the tree are the different possible realisations of the variables, each with a specified probability (i.e., likelihood); for example, a low wind damage has a probability of 0.05. The joint probability

Fig. 4. Probabilistic tree for house loss from fire attack (unpublished and preliminary; FIRE-DST project February 2012). The solid line shows a single possible outcome derived through the probabilistic tree. Dashed lines indicate links to other branches of the probabilistic tree that are not shown in this diagram.
of a particular outcome (each terminal node in the tree) is found by multiplying the probabilities of all the branches that constitute the path to that outcome (Hasofer et al. 2007). An example of a possible outcome in the probabilistic tree for the loss of a building due to several variables (wind damage, fire intensity, ember intensity, ember density, distance to other houses, number of fire fronts and shielding) is displayed in Fig. 4 as the solid line. An overall damage outcome for a population of houses is estimated by running the logic tree model through a number of iterative cycles to converge on the resulting damage estimate for the event.

Impact analysis
Impact is the set of consequences from a particular event. Consequence can be defined as the ‘outcome of an event affecting objectives’. The terms ‘consequence’ and ‘impact’ therefore have an identical meaning (NEMC 2010). The categories of impact in the framework are drawn from NEMC (2010), (Fig. 1). Impact is calculated as follows. The hazard model generates a fire front that propagates through the landscape. The hazard model determines the location of the fire front at any time and its intensity as it attacks exposed assets. Vulnerability and cost models are driven by these levels of intensity and their conditional probabilities. The direct impact of the event is calculated from the costs modelled across all exposures during the event.

Risk analysis
The framework emphasises the distinction between risk and impact. Risk is intrinsically associated with likelihood. A computational risk analysis will run many fire impact event scenarios, each with its own likelihood of occurrence and impact. To gain a full understanding of risk, the modelled scenario events need to span a large range of likelihood and consequence.

The risk metrics produced by the risk analysis must, by definition, incorporate units of likelihood and consequence. These requirements are met when representing the results of the risk analysis in an exceedance probability (EP) curve. This curve relates the likelihood of fire events to the maximum potential impact associated with them (Fig. 5). The EP curve slopes down from left to right and illustrates, in general, that there will be many more events with high likelihood and low impact than rare events with high-impact.

A bushfire EP curve quantifies a risk profile for the analysis area, based on the hazard, exposure and associated vulnerabilities in that particular area. The extreme right of the curve represents the probable maximum loss (PML) event, with credible losses potentially greater than the most severe event that the area has experienced historically. The curve also allows estimation of the loss for an event of any likelihood level or return period by projecting that likelihood level to a point on the curve and reading off the resultant impact. The average annualised loss corresponds to the area beneath the EP curve and represents the average annual cost to exposed communities. The quantitative statistics derived from the EP curve, such as the average annualised loss, the PML and return period losses, all underpin the development of risk management strategies based on evidence not only from historical events, but also considering the full range of potential future events. For example, the EP curve and its derived statistics directly quantify the effectiveness of mitigation measures that affect the risk profile of an area, for example through changes to building codes or land-use planning.

Dealing with uncertainty in the generated risk analysis
It is important to track, estimate, and report uncertainties in quantitative bushfire impact or risk analysis. Users of the risk information gain valuable knowledge about the limits of what is known and not known from the estimates of uncertainty in their risk analysis, and can make risk management decisions aided by this knowledge.

Two kinds of uncertainty are important in impact and risk modelling:

- **Aleatory uncertainty** refers to the natural randomness of natural phenomena; it can be estimated but cannot be reduced. Aleatory uncertainty can be modelled by sampling random variables (Patchett et al. 2004; Sanabria and Cechet 2007).

- **Epistemic uncertainty** refers to our limitations in knowledge and can be associated with uncertainty in a model’s ability to adequately describe a natural process. Epistemic variability can be captured by using two or more different models to estimate impact or risk and using a weighted average of the results to produce a final result (e.g., Toro et al. 1997, Frankel et al. 2000). Epistemic uncertainty can be reduced by validating and improving risk analysis models.
Validation techniques for the modelled results

One of the benefits of the quantitative risk assessment framework is that the user can validate the modelled results by comparing output risk metrics against observations from historical and current events. EP curves for observed events can be constructed to validate the likelihood and severity distribution of modelled events if historic hazard and impact data are available. The comparison between historic and modelled events could be based on, e.g., financial loss, lives lost or number of assets destroyed.

It is important to validate results at different resolutions and in different geographical areas because the performance of models may vary with scale and location. For example, estimates of the aggregated potential losses for an entire State may seem reasonable, but model performance may be poorer in some parts of the State than others due to differences in data quality or variability of physical processes in complex terrain.

We mention two notes of caution about validating models against historical data. First, validating model performance for extreme events is not straightforward because it is difficult to estimate the likelihood of these events when observations may span only a few decades. However, it is essential for the user to carry out a ‘sanity check’ validation for modelled events with rare likelihoods. Second, historical losses need to be trended to reflect impact in current day dollars. This trend needs to account for changes in population, inflation and value of assets at a local/regional scale (e.g., Crompton and McAneney 2008). In addition there are a range of factors including social mores and prevention and preparedness activities that can vary community resilience to event impacts at a range of scales (Paton 2008).

Finally, we mention that it is critically important to collect post-disaster hazard and impact data systematically following severe and extreme fires in Australia. Improved forecasts of future extreme fire impacts depend on these data. The post-disaster data are used to validate impact and risk assessment models and improve estimates of uncertainty in the forecasts. For example, the characteristics in fire-spread models (e.g., rate of spread, radiation intensity and propagation of embers) can be improved by validating the models against prevailing fire weather and fuel properties during historic extreme fires. Similarly, improvements in vulnerability models can be demonstrated after they are validated against observed hazard impacts on exposed economic, societal and environmental assets. Improvements in hazard and vulnerability models can reduce epistemic uncertainty.

Conclusions

A new, quantitative bushfire risk assessment framework has been prepared to address the demand for improved bushfire risk information in Australia. The framework is a guide for Bushfire CRC researchers in social, environmental and economic areas of endeavour. It also provides best practice guidance for fire and planning agencies. The Bushfire CRC’s FIRE-DST project is currently in the process of implementing this framework to produce a model for the direct impacts of bushfires on building loss and mortality.

There are gaps in key datasets and models required for computational bushfire risk analysis at present, and the framework precedes the current ability of practitioners to assess all aspects of bushfire risk. Key gaps include datasets for fuel loading and condition and computational models for ignition likelihood, vulnerability, as well as risk.

A full implementation of the bushfire risk assessment framework should also consider impacts beyond those currently covered in FIRE-DST, i.e. direct losses of house and life. Additional impacts should include impacts associated with productivity loss, business disruption, emergency management and medical costs, as well as environmental and agricultural damage. The framework described in this paper incorporates all of these different aspects of bushfire impact into a consistent risk assessment approach that supports development of evidence-based risk management strategies. For example, the outputs of a product such as FIRE-DST can quantify the benefits and costs of a range of risk mitigation strategies such fuel reduction burns, resource allocation, community low-risk defendable regions and community education.

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References


