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Environmental circumstances surrounding bushfire fatalities in Australia 1901–2011

Raphaele Blanchi [a,b,*], *Justin Leonard* [a,b], *Katharine Haynes* [d], *Kimberley Opie* [c], *Melissa James* [a], *Felipe Dimer de Oliveira* [d]

[a] *CSIRO Ecosystem Sciences, Australia*
[b] *Bushfire Cooperative Research Centre, Australia*
[c] *CSIRO Land and Water, Australia*
[d] *Risk Frontiers Macquarie University, Australia*

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ABSTRACT

This paper describes the development and analysis of a dataset covering bushfire related life loss in Australia over the past 110 years (1901–2011). Over this time period 260 bushfires have been associated with a total of 825 known civilian and firefighter fatalities. This database was developed to provide an evidence base from which an Australian national fire danger rating system can be developed and has benefits in formalising our understanding of community exposure to bushfire. The database includes detail of the spatial, temporal and localised context in which the fatalities occurred. This paper presents the analysis of 674 civilian fatalities. The analysis has focused on characterising the relationship between fatal exposure location, weather conditions (wind speed, temperature, relative humidity and drought indices), proximity to fuel, activities and decision making leading up to the death.

The analysis demonstrates that civilian fatalities were dominated by several iconic bushfires that have occurred under very severe weather conditions. The fatalities from Australia's 10 worst bushfire days accounted for 64% of all civilian fatalities. Over 50% of all fatalities occurred on days where the McArthur Forest Fire Danger Index (FFDI) exceeded 100 (the current threshold for declaring a day as 'catastrophic') proximal to the fatality.

The dominant location category was open air representing 58% of all fatalities followed by 28% in structures, and 8% in vehicles (6% are unknown). For bushfires occurring under weather conditions exceeding an FFDI value of 100, fatalities within structures represented over 60% of all fatalities. These were associated with people dying while attempting to shelter mainly in their place of residence. Of the fatalities that occurred inside a structure in a location that was specifically known, 41% occurred in rooms with reduced visibility to the outside conditions. Over 78% of all fatalities occurred within 30 m of the forest.

* *Corresponding author at*: CSIRO Ecosystem Sciences, PO Box 56, Highett, Victoria 3190, Australia. Tel.: +61 392526194.
E-mail address: Raphaele.Blanchi@csiro.au (R. Blanchi).

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1. Introduction

The safety of communities exposed to bushfires is influenced by resident awareness, preparedness, responses and warning systems. In Australia, the existing Fire Danger Rating System is based on the McArthur Forest Fire Danger Index (FFDI). The FFDI relates the expected fire behaviour and rate of spread in common fuel types in eastern Australia (McArthur, 1967; Luke and McArthur, 1978) to the large-scale weather conditions and was originally developed to inform fire suppression activities. Its use has been extended to include a much broader range of applications including the implementation of community warnings.

Most of the studies on impact to community have occurred during post-bushfire surveys and subsequent survey analysis to better understand the mechanisms of bushfire attack at the urban interface (e.g. Barrow, 1945; Ramsay et al., 1987). The important points of consideration in those studies were how risk of loss was influenced by building design, the immediate landscape, the type of urban interface and human activity (e.g. Barrow, 1945; Ramsay et al., 1987; Leonard, 2003; Blanchi et al., 2006; Blanchi and Leonard, 2008).

Studies of human activities during bushfire have suggested that people sheltering in their house and implementing various protection strategies have a better chance of survival than people who expose themselves to radiant heat when evacuating late (McArthur and Cheney, 1967; Wilson and Ferguson, 1984; Krusel and Petris, 1999). Also it has been shown that active defence by residents or brigade members significantly increases the chances of house survival (Wilson and Ferguson, 1986; Leonard, 2003; Blanchi and Leonard, 2008). Based on the understanding that 'people protect houses and houses protect people' community safety bushfire policy in Australia was established around the 'Prepare, stay and defend or leave early' policy position (Australasian Fire Authorities Council, 2005). Under the policy residents were advised to prepare to stay and defend their home and property against bushfire or to leave well ahead of the arrival of a bushfire (e.g. Handmer and Tibbits, 2005; Tibbits et al., 2006; Handmer and Haynes, 2008; Haynes et al., 2010; Whittaker et al., 2013).

The policy was scrutinised during the 2009 Victorian Bushfires Royal Commission because a large number of people had perished within their homes (Teague et al., 2010). The Commission concluded that the 2009 bushfires exposed weaknesses in the way the policy was applied, and recommended the adoption of the national 'Prepare. Act. Survive.' strategy. The core messages of the strategy are very similar to the old policy, however, it stresses the safer option of leaving early, and the dangers and significant level of preparation needed for successful defence. The Commission also noted the increased risk to life and property on the worst fire days and recommended significant improvements to risk communication, education and warnings (Teague et al., 2010). The recommendations resulted in a review of the fire danger rating system and the development of the National Framework for Scaled Advice and Warnings to the Community (Australasian Fire Authorities Council, 2009).

The implementation of this new warning framework also triggered a review process to undertake a major evaluation of the current National Fire Danger Rating system. This review process identified the need to improve our understanding of the environmental circumstances that lead to life loss in bushfires. Few studies have specifically focused on the details of fatalities during bushfires. Krusel and Petris (1999) studied the circumstances of civilian fatalities during the 1983 Ash Wednesday bushfire. In a more recent study Haynes et al. (2010) analysed 552 civilian fatalities in bushfires from 1900 to 2008. The study explored the context of bushfire related fatalities and focused on the activities, behaviour and decision making carried out at the time of death. The study was able to verify and emphasise the danger of being caught outside during the passage of a bushfire. It also demonstrated a clear gender bias, with male fatalities most often occurring outside while trying to protect assets and female fatalities occuring inside while sheltering, or trying to flee (Haynes et al., 2010). O'Neill and Handmer (2012) also undertook a detailed study of the circumstances surrounding the 172 civilian deaths during the 2009 Victorian bushfires.

These studies have tended to focus on victim behaviour rather than the spatial and environmental circumstances of civilian fatalities. Notable exceptions include studies by Harris et al. (2012) and Kilinc et al. (2013), which explored the relationship between the power of the fire and community losses. Other studies have focused on the influence of environmental circumstances on house loss for individual bushfires (e.g. McArthur and Cheney, 1967; Ramsay et al., 1987; Leonard and Blanchi, 2005) and across multiple bushfires (e.g. Ahern and Chladil, 1999; Chen and McAneney, 2004, 2010; Blanchi et al., 2010; Harris et al., 2012).

This study therefore aimed to examine the environmental circumstances of civilian bushfire fatalities across all of Australia over the last 110 years. A database (Life Loss database) was generated using a specific data set that included spatial, temporal and the localised context in which the fatalities have occurred. This paper presents and discusses findings on the relationship between exposure location, weather conditions, proximity to fuel, and fatality activity and decision making leading up to the death. The various policy implications of these results for community safety are discussed.

2. Methodology

The Life Loss database was developed by collating different available data on bushfire related life loss in Australia over the past 110 years (1901–2011). A range of circumstances leading up to the fatal exposure were also captured, including: fire arrival time and severity, weather conditions, proximity to fuels, and activity defined by the decisions made before fatal exposure.

The most comprehensive listing of past fatalities provided was the Risk Frontiers Database 2011 (which covers fatalities Australia-wide). This dataset was initially developed by Risk Frontiers as part of PerilAus database (Crompton et al., 2011) and used by Haynes to develop a dataset of civilian fatalities up until 2008 for the Bushfire CRC (Haynes et al., 2010). This dataset was used as a basis for developing the Life Loss database which has been expanded to cover a total of 825 fatalities involving 733 civilians and 92 firefighters.

A number of different data sources were accessed in order to assemble the Life Loss database. These included coronial inquest records, national inquiry records (e.g. McArthur and Cheney, 1967; Ellis et al., 2004), royal commission reports (Teague et al., 2010),[1] journal papers (e.g. Wilson and Ferguson, 1984; Ramsay et al., 1987; Cheney et al., 2001), books (e.g. Cheney, 1979; Collins, 2009), post bushfire study reports (including fire behaviour, surveys, etc.), fire management and fire service reviews of major bushfires (e.g. Country Fire Authority, 1983; Krusel and Petris, 1999; NSW Rural Fire Service, 2000), the World Wide Web, newspaper articles sourced from libraries and state public records offices, memorials, discussions with various state-based fire agencies and personal communications with various fire agency personnel.

Different types of data have been compiled in the dataset: quantitative variables (e.g. weather information), and categorisation variables (e.g. location of fatality). Some information was categorised to facilitate spatial and statistical analysis. Other potentially useful information has been collected and left as open text such as addresses, and descriptions (e.g. death circumstances, building and surroundings, bushfire).

The uncertainty and variability in the data is often due to the different sources and quality of data available and the processes used to generate the data. The main causes of uncertainty and variability were lack of evidence or information to locate a fatality or categorise some of the information associated with it.

The analysis presented in this paper includes data collected on fatal exposure location, weather context, and proximity to fuel (forests).

2.1. *Fatal exposure location*

Information was collected on the fatality location, time and circumstances of death. The objective was to determine the location and time of exposure in order to spatially locate the fatality and to correlate this with other variables. The location of spatial features (fatal exposure location, houses, and vehicles) was derived using aerial imagery. In each case an error precision was associated with the location. The variability on reported bushfires and fatalities has an impact on the precision of fatal exposure and other objects location.

The location of fatal exposure was also coded in four categories:

- inside structure,
- inside vehicle,
- open air, and
- unknown.

In addition, a detailed description of the location of the fatal exposure was recorded for each fatality where sufficient information was available (e.g. the room where fatalities occurred, position in vehicle, precise distance from vehicle, or other relevant spatial information).

Other categories used in the analysis were built upon the coding scheme developed by Haynes et al. (2010):

- Sex: categories indicating gender of person (male, female, unknown),
- Age class: categories indicating age group of person,
- Activity prior to fatality: categories indicating the activity prior to death (e.g. sheltering, defending, evacuating), and
- Decision making: categories indicating the fire plan and decisions taken by a fatality.

2.2. *Weather context*

The meteorological data compiled in the dataset and used in the analysis came from various reports (e.g.Foley, 1947; McArthur and Cheney, 1967) and from standard synoptic observations made by the Australian Bureau of Meteorology. Weather information was attributed to individual fatalities based on the bushfire in which the death occurred (at time of fatal exposure or 3 pm). A bushfire is defined as an unplanned fire resulting from a particular origin (note: several bushfire events can occur on one day).

The number and type of meteorological records for each fire was dependant on the availability of data. Meteorological data was recorded at different times throughout the day at different nearby weather stations. The two sources of data used were:

- Weather station observations from the Bureau of Meteorology, and
- The historical fire weather dataset described by Lucas et al. (2007); Lucas (2010); Blanchi et al. (2010).

The FFDI calculation was based on the McArthur Forest Fire Danger Index meter Mark5 (McArthur, 1967; Luke and McArthur, 1978). The basic equations came from Noble et al. (1980). The FFDI was originally developed for fire management purposes and relates the expected fire behaviour and rate of spread in common fuel types in eastern Australia (McArthur, 1967; Luke and McArthur, 1978). It is also used to provide a basis for forecasts, community warnings and setting of fire intensity for urban design in Australia (Standards Australia, 2009).

In this study the FFDI was used to characterise the fire weather intensity and its potential for destruction, and has been used in other studies for precisely that purpose (Bradstock and Gill, 2001; Blanchi et al., 2010; Harris et al., 2012).

2.3. *Proximity to fuels*

Different sources of spatial information were used to determine the environmental circumstances such as the location and extent of objects directly related to a fatality. This includes vegetation, fire isochrones and fire severity layers.

The National Carbon Accounting System (NCAS) forest/non-forest (FNF) dataset was used to determine the distance to forest and surrounding forest density from a fatal exposure location where this data was available. The NCAS FNF products are

[1] http://www.royalcommission.vic.gov.au/commission-reports/final-report (accessed September 2013).

binary images developed for the purposes of tracking forest extent and monitoring deforestation and reforestation. Forest is defined according to the National Forest Inventory as vegetation with a minimum 20% canopy cover, potentially reaching 2 m high and a minimum area of 0.2 hectares. The straight line distance from the fatal exposure location to the closest forest was calculated. For the spatial analysis, the forest layer of the closest preceding year to the fire was used to determine the distance to forest. It is assumed that the layer which coincides with the year of the fire may have a forest extent affected by the fire scar. The distance to forest was not recorded where the preceding year data was not available.

3. Results and discussion

The Life Loss database refers to fatalities between 1901 and 2011 (inclusive) during which time the average rate of civilian deaths was 6.6 per year. The analysis presented in this paper focused on the civilian fatalities that have occurred as a direct result of bushfire impact (smoke, radiant heat flux, convection, direct flame contact, heat stress), which represents 674 civilian fatalities (59 fatalities that were indirectly related to the fire, unknown or unclear were not included in the analysis). This segregation was to improve the statistical relevance of how proximity and severity of fire mechanisms influence life loss. For some of the analysis the data is presented according to three time periods; for the entire time period of data, pre 1965, and post 1965. This segregation of data also happened to be useful in distinguishing some patterns over the years, and provided an opportunity to compare demographic context relating to social behaviour and prevalence of technologies such as automobiles.

The analysis focused on:

- The spatial locations of all fatalities in Australia. The fatalities' location categories (inside structure, inside vehicle, open air, unknown) were examined to determine if there was any relationship with other variables (e.g. activity, decision making and weather context),
- The relationships between the fatalities, the location of fatal exposure and the fire weather conditions under which the fire occurred were examined using the McArthur FFDI and its components at 3 pm and at time of exposure if available (Luke and McArthur, 1978; Noble et al., 1980). Other aspects of weather such as wind changes were also explored,
- The activity and decision making were examined in relation to other circumstances such as fatal exposure location and weather context using multivariable analysis, and
- The relationships between the fatalities, their location and proximity to forest, were examined. (Note: The fatality locations with an uncertainty greater than 100 m were removed from this analysis.)

3.1. *Demographics*

The number of fatalities varied greatly in each state with 67% of all fatalities having occurred in Victoria (see Fig. 1). There is

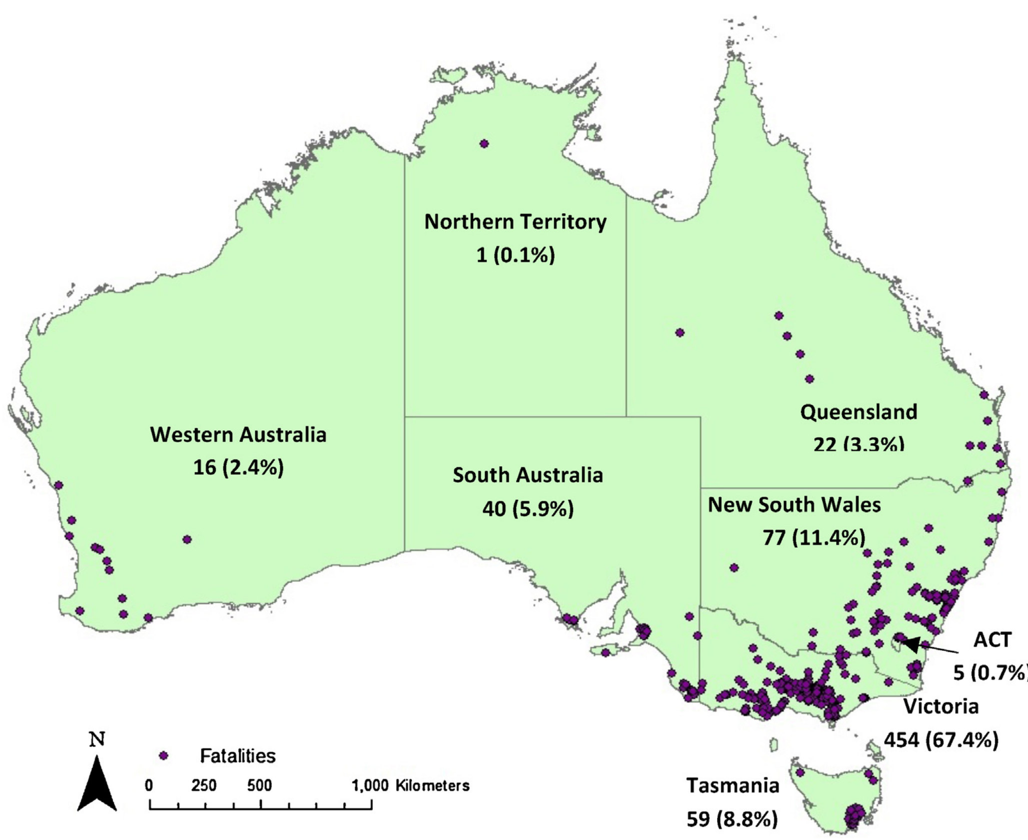

Fig. 1 – Loss profile by state and specific location (purple dots) of all civilian fatalities in Australia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

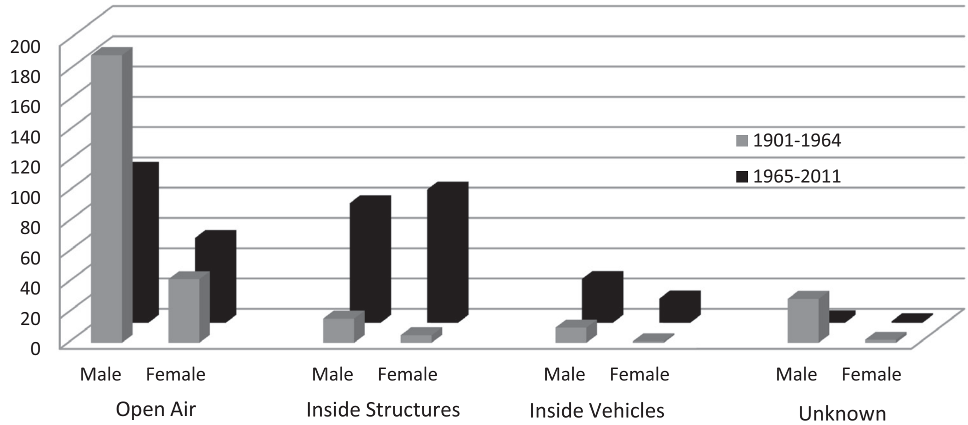

Fig. 2 – Location of fatal exposure for civilian fatalities and comparison with gender (between 1901–1964 and 1965–2011).

a clear trend for fatality rates to decrease when moving further north into the more tropical climate zones as climate conditions are less favourable to severe fire. There is also a clear concentration of loss around population centres in the south.

The gender distribution of civilian fatalities was studied to help inform specific trends relating to assumed behaviours or activities. The gender role could demonstrate an evolution of behaviour in the different roles of men and women over the century. Fig. 2 shows the distribution of fatality locations by gender for pre and post 1965. The proportion of males dying in earlier fires (82.2%) was significantly greater than the proportion dying in recent fires (56.1%) in accordance with the findings of Haynes et al. (2010).

Fifteen major fires (out of 260 fires included in the database) involving 9 or more fatalities per fire represented 53% of all civilian fatalities. These fires have occurred during 10 fire days and are detailed in Table 1. The total number of fatalities during those days accounted for 64% of all civilian fatalities. Over 87% of civilian fatalities have occurred in the months of January and February. Of these deaths the fatalities generally occurred in daylight with a peak between 3 pm and 7 pm.

3.2. *Location*

A description of the location of fatal exposure was recorded. For 92 cases the death occurred after the fire event at a distant location (e.g. in hospital). For these cases both a location of fatal exposure and a location of death were recorded. The location and time of fatal exposure were used later to correlate circumstances such as weather and proximity to fuel as this location best reflected the conditions that lead to the death.

The location of fatalities were categorised into 'inside structure', 'inside vehicle' and 'open air' to understand the role

Table 1 – Ten major fire days in Australia involving 434 of all fatalities (civilian fatalities directly impacted by bushfire).

Date of fire	Number of civilian fatalities[a]	Number of bushfires[b]	Number of house loss[c]	Major bushfires >9 civilian fatalities (total number of civilian affected)	Weather context
14/02/1926	30	7	550	Gippsland – VIC – Gilderoy and Powelltown (16)	FFDI 67. Described as "hot North wind"
10/01/1939	19	2	650 houses reported for all 1939 fires	Black Friday bushfires – VIC – Rubicon (12)	FFDI 72–100
13/01/1939	46	12	650 houses reported for all 1939 fires	Black Friday bushfires – VIC – Matlock (22), Tanjil (9)	FFDI 74–100
14/01/1944	22	11	Around 700 for all 1944 fire	Linton – VIC (12)	FFDI around 100–150
14/02/1944	13	2	Around 700 for all 1944 fire	Morwell bushfires – VIC (9)	FFDI 66
7/02/1967	57	1	1257	Black Tuesday, Hobart – TAS (64)	FFDI 95 (reported 85)
8/01/1969	19	3	230	Lara – VIC (18)	FFDI 134
16/02/1983	25	2	383	Ash Wednesday – SA – Narraweena (14), Adelaide Hills (13)	FFDI 130
16/02/1983	33	5	2060	Ash Wednesday – VIC – Beaconsfield (9), Warrnambool (9)	FFDI 145
7/02/2009	168	5	2021	Black Saturday – VIC – Kilmore East (120), Murrindindi (39), Churchill (11)	FFDI 155

[a] Civilian fatalities directly related to bushfire impact.
[b] A bushfire is defined as an unplanned bushfire resulting from a particular origin. Note that several bushfires can occur on one day.
[c] Number varies according to sources.

of shelter at time of death. Fig. 2 shows the demographic of fatalities for each of these categories. For civilian fatalities found inside structures 51% were male and 49% were female. For civilian fatalities found inside vehicles 70% were male and 30% female. For civilian fatalities in the open air 75% were male and 25% female. The proportion of male deaths in open air was even greater in the first half of the century; see Haynes et al. (2010) for further details. This is possibly related to job profiles that involved remote location work such as timber felling where shelter was not easily accessible or farmers attempting to save livestock. A significantly greater proportion of fatalities occurred inside structures or inside vehicles in recent fires (44% inside structure for the period 1965–2011), compared to earlier fires (7.1% inside structure for the period 1901–1964). The higher proportion of fatalities inside vehicles in the time period 1965–2011 (12% in 1965–2011 period compared to 3.7% in 1901–1964 period) is explained by higher prevalence of cars and their use during this period.

For the fatalities that occurred inside structures it is useful to understand the location within the structure in which the fatal exposure occurred, as this assists in understanding the behaviour adopted and how the house may have lost its tenability. The detailed study of the location of 188 fatalities inside a structure showed that 37% of the fatalities with known locations occurred in a room with reduced visibility to outside conditions (bathroom, laundry, study, toilet block, bunker) and for 34% of fatalities the location was unknown. All other cases (29%) either involved an opportunity to monitor outside conditions or were adjacent to an exit to facilitate egress when the house approached untenable conditions. Similarly, the study of the 1983 Ash Wednesday fire in Victoria (Krusel and Petris, 1999) and the study of the 1967 Hobart fire (McArthur, 1967) showed that the small number of fatalities that occurred inside a house mainly involved occupants sheltering in a closed room (e.g. bathroom) with no clear view of the circumstances outside of the structure.

3.3. *Fire weather*

The relationship between fatal exposure and fire weather is explored in this section. The range of data recorded varied from qualitative information from reports or inquests, to quantitative information on weather conditions at different times of the day (time of exposure and 3 pm observations).

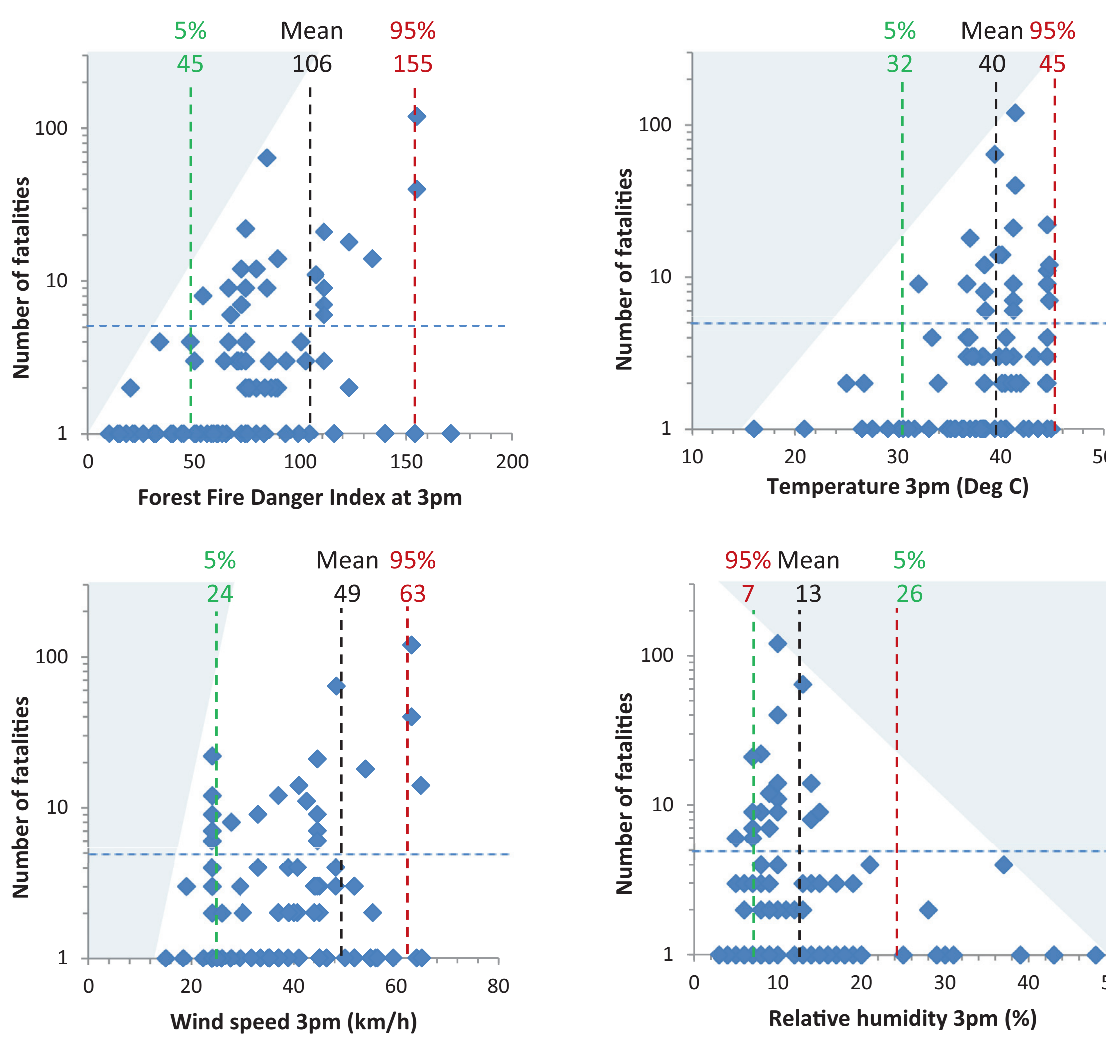

Fig. 3 – Relationships between the number of fatalities (logarithmic scale) and FFDI at 3 pm, temperature, wind speed and relative humidity. The blue dotted line represents the threshold for five or more fatalities. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

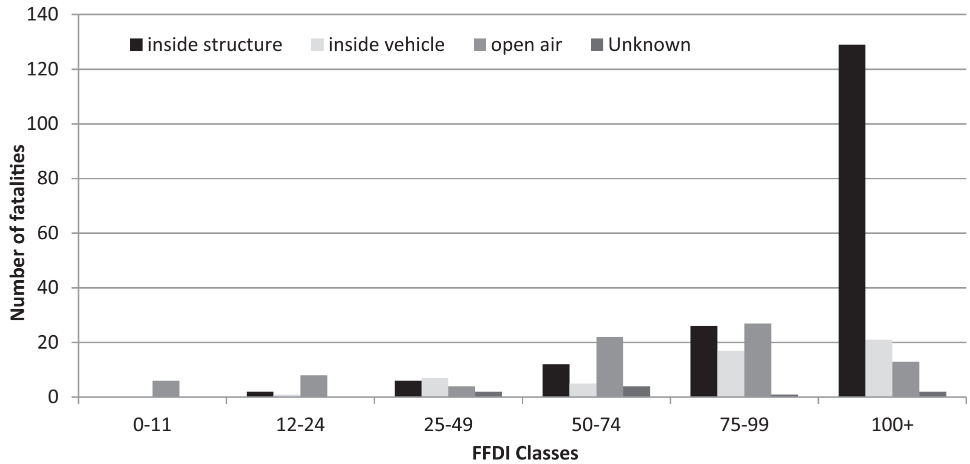

Fig. 4 – Location of fatal exposure and Forest Fire Danger Index class at 3 pm (classes used in current weather warning[2]).

Standard meteorological observations at 3 pm, and data from the historical fire weather dataset described by Lucas (2010) were obtained for 114 fires.

The 3 pm FFDI and the FFDI at time of exposure were used to represent the weather conditions during the fire. Using FFDI at a fixed time of the day may not be representative of the weather conditions most influential during the fatal exposure. For example, by taking into account the summertime cool change, which may have occurred before or after the time considered in the analysis. The summertime cool change often crosses southern Australia during the day and is associated with an abrupt drop in temperature, rising relative humidity (RH) and wind direction and strength changes (Luke and McArthur, 1978). A summertime cool change was associated with 53% of civilian fatalities (358), with 90% appearing to have died shortly after the change and 10% before the change.

The time of exposure in relation to the cool change makes a distinctive difference in FFDI value, as weather conditions are relatively mild after the cool change, with temperatures typically much lower than at 3 pm (note that 75% of exposures occurred after 3 pm). It is interesting to note that in those cases the FFDI value at time of exposure might not represent the weather conditions at the fatal exposure location. Several reasons could be envisaged: high local winds are associated with the changes that might not be recorded at the weather station (Luke and McArthur, 1978 and anecdotal evidences) and fuel moisture lag (which correspond to the time delay for fuel moisture content to respond to change in environmental conditions).

It is difficult however, to determine a time when weather conditions are representative of the peak weather experienced by the person exposed. Ideally using the peak FFDI of the day (on an hourly basis) would reduce the inconsistency in using a fixed time. However this data was not consistently available across the time scale in which fatalities have occurred.

Weather severity based on 3 pm figures provides an important context for fatal exposure. Fig. 3 below shows the numbers of fatalities against specific weather parameters. The mean, 5th and 95th percentile weather values are also provided and shown as vertical lines. Fig. 3 displays the relationship between the number of fatalities per fire (on a logarithmic scale) and weather variables at 3 pm (FFDI, temperature, wind speed and relative humidity) based on 93 observations.

These graphs can be particularly useful in deriving thresholds for the conditions above which significant losses of life per fire have occurred. The shaded regions in each of the plots in Fig. 3 are clear regions where no losses were recorded. Regions such as these can serve as a sound basis for establishing appropriate weather severity thresholds for policy implementation. As an example the five fatalities per fire line is drawn for each graph (blue dotted lines on Fig. 3). For FFDI the plot shows that the lowest FFDI for a fire involving five or more fatalities occurred for an FFDI above 50 and its intersect with the shaded region occurred around an FFDI of 35. For the other weather parameters the minimum temperature in which 5 or more losses occurred was 33 degrees Celsius, minimum wind speed was 24 and maximum relative humidity was 16%.

To better understand the impact of fire severity on fatalities, the location of fatal exposure was compared to the class of FFDI. Fig. 4 clearly shows the high prevalence of deaths inside structure in the value of FFDI of 100 plus category (fire danger rating 'catastrophic'). The context of the fire weather severity in understanding the location of death is important with a significant shift from open air fatalities at low FFDI's to a dominance of inside structure deaths at FFDI's greater than 100.

3.4. *Activity and decision making*

The relationship between activity, decision making and Forest Fire Danger Index (FFDI) at 3 pm has been studied using a tridimensional probability visualisation (Fig. 5). The probability distribution of the three variables of interest: activity, decision making and FFDI was determined by

[2] http://www.bom.gov.au/weather-services/bushfire/index.shtml (accessed February 2013).

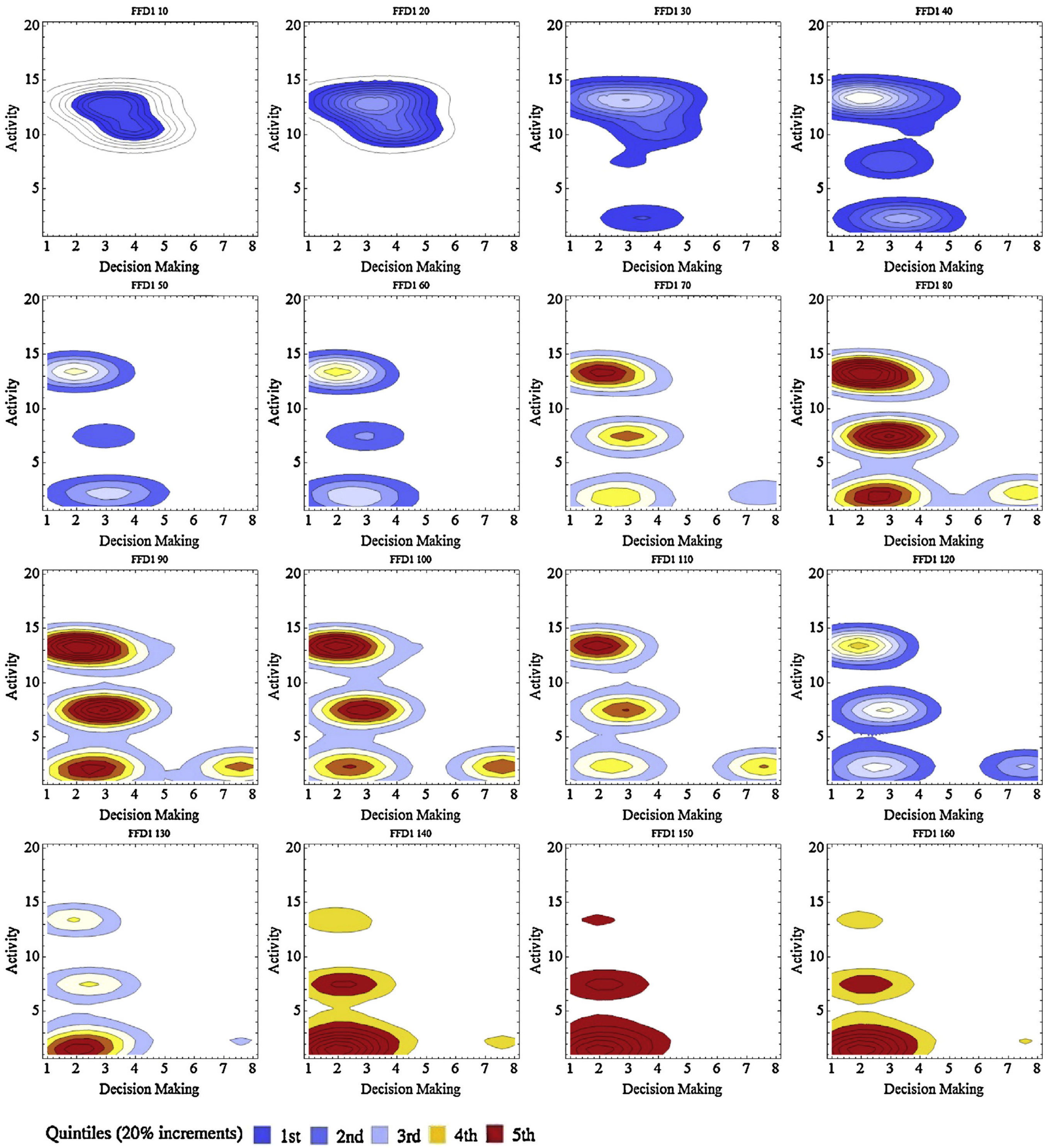

Fig. 5 – Tridimensional probability visualisation of the variables decision making, activity and FFDI (at 16 different values of FFDI). The data is distributed across categories, from dark blue (representing the lowest density of data, 0–20% of fatalities) to dark red which represent the highest density of data (representing 80–100% of fatalities in this category).

applying a kernel smoothening technique that transforms each point in the event space into a ''cloud'' and adds them together. In this way, regions with larger number of points have more ''clouds'' superimposed, resulting in a larger value for the probability mass.

This probability distribution can be visualised by performing tomography, that is, by plotting cross sections of this distribution. In this case, the probability in a plane perpendicular to the ''upward'' variable (FFDI) was cut (which are represented for visualisation by the 12 tiles in Fig. 5 corresponds to a constant

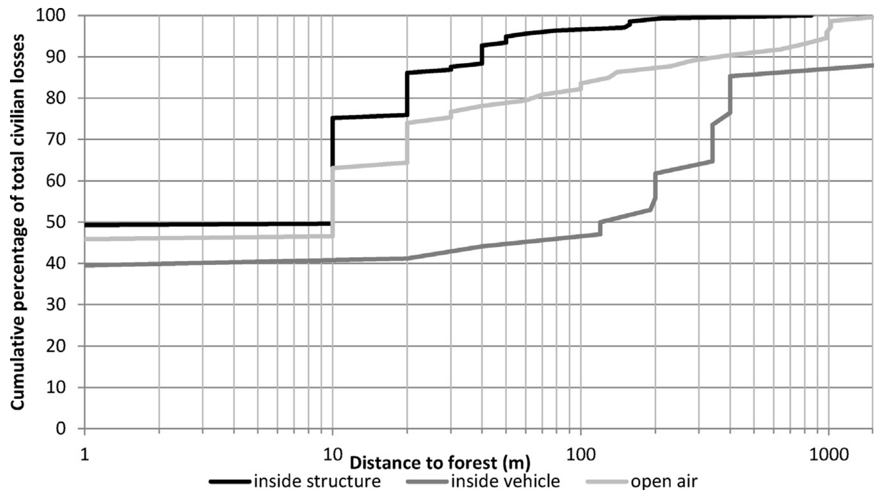

Fig. 6 – Cumulative loss profile of fatalities distance to closest forest (per location categories).

value of FFDI, for which the probability is encoded in the colour scheme (red, or "hot" regions have higher probability) as a function of the "x" (decision making) and "y" variables (activity). A full image of the distribution is obtained by "stacking" plots of increasing FFDI, with the fourth dimension (the probability) shown as the colour intensity.

In summary, the activity codes between 1 and 6 represent people sheltering, the codes from 7 to 9 are fatalities evacuating, codes 10 to 13 are fatalities travelling (for saving own property or for pleasure), and 14 is outside (e.g. saving livestock). Decision making is coded from 1 (fatalities that had a plan that was ineffective), 2 (aware of the fire but plan unclear), 3 (unaware of fire), 4 (unknown), 6 (children or adults who followed the instructions of another person) to 7 (physically or mentally incapable of implementing an effective survival strategy).

Fig. 5 indicates that fatalities that occured during lower FFDI (corresponding to the first 4 tiles) were associated with people who were defending wider property or were caught outside in highly exposed positions. Many of these people did not have plans or were unaware of the fire until it was too late to implement a successful survival strategy. Moderate FFDI's were associated with a range of activities including defending wider property, late evacuation and sheltering with some defence. These people were split between those who had plans and were carrying out a premeditated action and those who did not have a plan, and those with a firm plan but did not follow their plans. Extreme FFDI was associated with those sheltering (including defending) at the time of death and also included in higher numbers those who had a plan and were carrying out a premeditated action (mainly for 2009 Victorian bushfires).

3.5. *Proximity to fuel*

The separation between bushfire fuels and the fatality is an important risk assessment metric to classify likely exposure levels on the person, vehicle or structure used by several studies on house loss (Ahern and Chladil, 1999; Chen and McAneney, 2004, 2010; Newnham et al., 2012).

The distance from forest to fatalities inside a structure (137), inside a vehicle (34), and in open air (73) is shown in Fig. 6. A distinctive profile was present for fatalities within structures, where 76% of fatalities have occurred within 10 m of the forest, 88% within 30 m and 95% within 50 m. This suggests that fatalities within structures were strongly associated with high radiant heat and possible flame contact circumstances which possibly contributed to a rapid rate of tenability loss of the structure. Comparing these percentages with the broader dataset of house loss as a function of distance to forest (Newnham et al., 2012) demonstrates that house loss involving fatal exposure were far more dominant in the 0–30 m distance from forest regions. Compared to house losses not involving fatalities, less than 60% of all house losses occurred less than 30 m from the forest.

4. Conclusion

The database developed in this work integrates the spatial, temporal and the localised context in which fatalities have occurred. An extensive range of qualifying parameters has also been included to assist in developing the context under which the deaths occurred. The database contains details of fire weather severity (using FFDI and its individual components), fire behaviour, proximity to forest, incident circumstances, fatality details, activities and the location of objects and structures related to the fatality. The spatially explicit nature of this dataset allows a wide range of analysis to be undertaken. The analysis presented in this paper focused on a subset of this range limited to the relationship between location of fatal exposure, activities and environmental circumstances such as weather conditions and proximity to forest fuel.

The study has provided a better understanding of life loss circumstances and the specific threats experienced by communities exposed to bushfire. In particular the analysis has shown that the fire weather severity is an important qualifier in setting the context of life loss, with mean values for all weather parameters for all civilian fatalities occurring on days with the following conditions: FFDI values above 105, temperature exceeding 39 °C, relative humidity below 13%, and wind speeds greater than 48 km/h. In fact, 50% of civilian fatalities have occurred during days when the 3 pm FFDI exceeded 100, conditions which are now termed 'Catastrophic'.

Statistical analysis demonstrated a tendency for fatalities on moderate fire weather days to occur while defending property, evacuating late or sheltering with some defence. This group consisted of a mix of people with and without fire plans. On the most severe fire weather days, fatalities mostly involved those who sheltered and followed a pre-considered plan. Fatalities within structures were the most prevalent for FFDI values above 100.

Proximity to forest was a strong qualifier of fatalitiy potential with over 78% of fatal exposures occurring within 30 m and 85% within 100 m of the forest edge. Fatalities occurred in various locations: 58% in the open air, 28% inside structures, 8% inside vehicles and 6% unknown. Male and female civilian fatalities within structures were evenly represented, while male fatalities out in the open were approximately 3 times greater. The better understanding of the location of fatalities within structures raises several questions in relation to egress, sheltering and the rate of loss of tenability of houses. A house may lose tenability quicker than is anticipated by its occupants, who may not know how to monitor the status of the house they are sheltering in. In some cases it may be inferred that occupants believed that there was no option to leave a burning house, believing it even more risky to leave. This highlights the need for better community education on sheltering and being aware of outside conditions. This study demonstrated that under extreme weather circumstances staying in the house should be considered carefully in conjunction with the physical circumstances of the property and personal resident preparation (Penman et al., 2013). Residents are now advised in Victoria under 'catastrophic' conditions to leave early and significant emphasis is now made of the dangers of defending and the preparation needed. However, it is worth noting that a survey of resident preparation and response during 2009 Victorian bushfires found that 77% of houses that were defended by one or more people survived the fires (Whittaker et al., 2013).

Fatalities were dominated by a few bushfires that have occurred under catastrophic weather conditions. These conditions should be used as the context for discussing appropriate defensive actions for communities faced with a bushfire threat. In this regards warning systems play an important role providing timely information on the weather context and potential fire severity to assist residents decision making (e.g. what decision to take under a certain FFDI level in the current system). However, it is questionable whether improved and more detailed warnings would lead to a significant improvement in community safety. Research has demonstrated that people often adopt a 'wait and see' approach, either waiting for confirmation that they will be threatened or to see what the fire is like before deciding what to do (Tibbits et al., 2008; Whittaker and Handmer, 2010; McLennan et al., 2012). This may leave people with few options other than a late and potentially dangerous evacuation, or to remain at their home. For those who are not prepared to defend, as was the case for many of those who perished within homes in 2009, their last resort is to shelter. Sheltering passively is certainly a dangerous option, however, the advice surrounding how to do it in the most effective and safest way needs to be improved. This includes better information about: triggers to recognise the signs of the arrival of the fire front; when to seek shelter in the house; how to recognise when the house is no longer a safe refuge; when and where to exit; and where to go once outside the home. This information must be addressed through further research, policy reform, community education initiatives and associated warnings.

The findings presented in this paper have a number of implications for bushfire safety policy. They will help agencies to provide better warnings and information to the public (such as National Fire Danger Rating System) and to engage communities in awareness and education programmes that encourage preparedness and safe responses. In Australia, policies such as 'Prepare. Act. Survive.' (Australasian Fire Authorities Council, 2009) have enhanced the shared responsibility of risk between residents and fire services. Residents are asked to evaluate the risk and decide on the appropriate response. However the implications of these decisions and actions can lead to dramatically different outcomes if residents do not understand the risk and environmental context they may be confronted with. The findings of this study provide a substantial knowledge base to inform the development of policies, programmes and advice that will increase community safety during bushfire events.

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REFERENCES

Ahern, A., Chladil, M., 1999.In: How far do bushfires penetrate urban areas? Proc. Australian Disaster Conf. 1999 Disaster Prevention for the 21st Century. Canberra, Emergency Management Australia, pp. 6–21.

Australasian Fire Authorities Council, 2005. Position paper on bushfires and community safety. .
Australasian Fire Authorities Council, 2009. Prepare. Act. Survive.
Barrow, G.J., 1945. Survey of houses affected in the Beaumaris fire, January 14, 1944. Journal of the Council for Scientific and Industrial Research 18 (1) .
Blanchi, R., Leonard, J., 2008. Property safety: judging structural safety. In: Handmer, J., Haynes, K. (Eds.), Community Bushfire Safety. CSIRO Publishing, Melbourne, pp. 77–85.
Blanchi, R., Leonard, J., Leicester, R.H., 2006.In: Lessons learnt from post bushfire surveys at the urban interface in Australia. V International Conference on Forest Fire Research, D. X. Viegas, Figueira da Foz.
Blanchi, R., Lucas, C., Leonard, J., Finkele, K., 2010. Meteorological conditions and wildfire-related house loss in Australia. International Journal of Wildland Fire 19, 914–926.
Bradstock, R.A., Gill, A.M., 2001. Living with fire and biodiversity at the urban edge: in search of a sustainable solution to the human protection problem in southern Australia. Journal of Mediterranean Ecology 2, 179.
Chen, K., McAneney, J., 2004. Quantifying bushfire penetration into urban areas in Australia. Geophysical Research Letters 31 (12) L12212.
Chen, K., McAneney, J., 2010. Bushfire Penetration into Urban Areas in Australia: A Spatial Analysis, Risk Frontiers Report to the 2009 ''Black Saturday'' Bushfire Royal Commission Enquiry. .
Cheney, N.P., 1979. Bushfire disasters in Australia 1945–1975. In: Heathcote, R.L., Thom, B.G. (Eds.), Natural Hazards in Australia. Australian Academy of Science, Canberra, pp. 72–93.
Cheney, P., Gould, J., McCaw, L., 2001. The dead-man zone – a neglected area of firefighter safety. Australian Forestry 64 (1) 45–50.
Collins, P., 2009. Burn: The Epic Story of Bushfire in Australia: with an Introduction on the Black Saturday Fires. Scribe Publications, Melbourne.
Country Fire Authority, 1983. The major fires originating 16th February, Report CFA. .
Crompton, R.P., McAneney, K.J., Chen, K.P., Pielke, R.A., Haynes, K., 2011. Influence of location, population, and climate on building damage and fatalities due to Australian bushfire: 1925–2009. Weather Climate and Society 3 (1) 63–66.
Ellis, S., Kanowski, P., Whelan, R., 2004. National Inquiry on Bushfire Mitigation and Management. Commonwealth of Australia, Canberra.
Foley, J.C., 1947. A study of meteorological conditions associated with bush and grass fires and fire protection strategy in Australia. Bulletin no. 38. Commonwealth of Australia, Bureau of Meteorology, Melbourne234.
Handmer, J., Tibbits, A., 2005. Is staying at home the safest option during bushfires? Historical evidence for an Australian approach. Environmental Hazards 6 (2) 81.
Handmer, J.W., Haynes, K., 2008. Community bushfire safety. CSIRO Publishing, Collingwood, Vic.
Harris, S., Anderson, W., Kilinc, M., Fogarty, L., 2012. The relationship between fire behaviour measures and community loss: an exploratory analysis for developing a bushfire severity scale. Natural Hazards 63 (2) 391–415.
Haynes, K., Handmer, J., McAneney, J., Tibbits, A., Coates, L., 2010. Australian bushfire fatalities 1900–2008: exploring trends in relation to the prepare, stay and defend or leave early ''policy.'' Environmental Science & Policy 13 (3) 185–194.
Kilinc, M., Anderson, W., Anderson, D., Price, B., 2013. On the need for a bushfire scale that represents the bushfire hazard. Monash University Bushfire CRC Report to DSE, Melbourne.
Krusel, N., Petris, S., 1999. A Study of Civilian Deaths In the 1983 Ash Wednesday Bushfire Victoria. CFA Occasional Paper No 1. Contry Fire Authority, Mt Waverley28.
Leonard, J., Blanchi, R., 2005. Investigation of bushfire attack mechanisms involved in house loss in the ACT Bushfire 2003. CSIRO Manufacturing & Infrastructure Technology.
Leonard, J.E., 2003. People and property – a researcher's perspective. In: Cary, G., Lindenmayer, D., Dovers, S. (Eds.), Australian Burning: Fire Ecology, Policy and Management Issues. CSIRO Publishing, Melbourne, Vic.
Lucas, C., 2010. A historical fire weather dataset for Australia. Australian Meteorological and Oceanographic Journal 60, 1–14.
Lucas, C., Hennessy, K., Mills, G., Bathols, J., 2007. Bushfire Weather in Southeast Australia: Recent Trends and Projected Climate Change Impacts, Consultancy Report prepared for The Climate Institute of Australia. Bushfire CRC. .
Luke, R.H., McArthur, A.G., 1978. Bushfires in Australia. Reprinted with Corrections 1986. Canberra Publishing and Printing Co..
McArthur, A.G., 1967. Fire behaviour in eucalypt forests. Leaflet No. 107. Comm. of Australia For. Timber Bur..
McArthur, A.G., Cheney, N.P., 1967. Report on the Southern Tasmanian Bushfires of 7 February 1967. Forestry Commission Tasmania, Hobart.
McLennan, J., Elliott, G., Omodei, M., 2012. Householder decision-making under imminent wildfire threat: stay and defend or leave? International Journal of Wildland Fire 21 (7) 915–925.
Newnham, G.J., Siggins, A.S., Blanchi, R.M., Culvenor, D.S., Leonard, J.E., Mashford, J.S., 2012. Exploiting three dimensional vegetation structure to map wildland extent. Remote Sensing of Environment 123, 155–162.
Noble, I.R., Bary, G.A.V., Gill, A.M., 1980. Mcarthur fire-danger meters expressed as equations. Australian Journal of Ecology 5 (2) 201–203.
NSW Rural Fire Service, 2000. 50 years of fires in NSW New South Wales Rural Fire Service Printed. .
O'Neill, S.J., Handmer, J., 2012. Responding to bushfire risk: the need for transformative adaptation. Environmental Research Letters 7. (1) .
Penman, T.D., Eriksen, C., Blanchi, C., Chladil, R., Gill, M., Haynes, M., Leonard, K., McLennan, J., Bradstock, J.K., 2013. Defining adequate means of residents to prepare property for protection from wildfire. International Journal of Disaster Risk Reduction (in press, Available online 13 September 2013).
Ramsay, G.C., McArthur, N.A., Dowling, V.P., 1987. Preliminary results from an examination of house survival in the 16 February 1983 bushfires in Australia. Fire and Materials 11, 49–51.
Standards Australia, 2009. AS 3959-2009 (Amend. 1) Construction of buildings in bushfire prone areas, Standards Australia. .
Teague, B., McLeod, R., Pascoe, S., 2010. 2009 Victorian Bushfires Royal Commission final report: summary. Available at http://www.royalcommission.vic.gov.au/finaldocuments/summary/HR/VBRC_Summary_HR.pdf. (accessed September 2013).
Tibbits, A., Blanchi, R., Gill, A.M., 2006. A Resident's experiences of the 2003 Canberra bushfire. Australasian Bushfire Conference, Brisbane.
Tibbits, A., Handmer, J., Haynes, K., Lowe, T., Whittaker, J., 2008. Prepare, stay and defend or leave early: evidence for the Australian approach. In: Handmer, J., Haynes, K. (Eds.), In

Community Bushfire Safety. CSIRO Publishing, Melbourne, pp. 59–71.
Whittaker, J., Handmer, J., 2010. Community bushfire safety: a review of post-Black Saturday research. Australian Journal of Emergency Management 25 (4) 7–13.
Whittaker, J., Haynes, K., Handmer, J., McLennan, J., 2013. Community safety during the 2009 'Black Saturday' bushfires: an analysis of household preparedness and response. International Journal of Wildland Fire 22 (6) 841–849.
Wilson, A.A.G., Ferguson, I.S., 1984. Fight or flee: a case study of the Mount Macedon bushfire. Australian Forestry 47 (4) 203–236.
Wilson, A.A.G., Ferguson, I.S., 1986. Predicting the probability of house survival during bushfires. Journal of Environmental Management 23, 259–270.