Fire prevention treatments to mitigate wildfire risk

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Doctor of Philosophy

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School of Biological Sciences

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Abstract

Wildfires can have devastating impacts on life, property and the environment. Increasingly people are living in areas that place them at risk from wildfires. Fire management agencies use a range of strategies to reduce wildfire risk. The aim of this thesis was to investigate the effectiveness of fire prevention and response treatments to mitigate wildfire risk in south-eastern Australia. This was achieved by (i) investigating the drivers of ignitions and the relationship between social and biophysical variables on the probability of ignition; (ii) determining if ignitions are equal or whether some ignition causes pose more risk than others; (iii) investigating the factors that influence the containment of wildfires; and (iv) determining the relative effectiveness of mitigation and response strategies to mitigate the risk of house losses.

The spatial patterns of wildfire ignitions were investigated at a bioregional scale in New South Wales and Victoria using generalised linear models and a combination of social and biophysical variables. Human-caused ignitions are the dominant source of ignitions for wildfires in south-eastern Australia. The number of accidental and deliberate ignitions increased with increasing population density and decreasing mean elevation. Lightning ignition probability increased as the number of hot days and mean elevation decreased which reflects that fewer lightning ignitions occurred in the western arid and semiarid areas. In future years, more ignitions are predicted in the coastal and hinterland areas due to population increases and climate change effects.

A dataset of wildfires that destroyed houses in New South Wales and Victoria was compiled to determine which ignition causes are more likely to result in destroyed houses and whether there are associated weather conditions that increase the probability of a destroyed house. Powerlines, lightning and deliberate ignitions are the main causes of wildfires that destroyed houses. Fire weather was an important driver for deliberate- and powerline-caused wildfires that destroyed houses with temperature, wind speed and forest fire danger index all significantly higher and relative humidity significantly lower \( (P < 0.05) \) on the day of ignition for wildfires that destroyed houses compared with wildfires where no houses were destroyed. For all powerline-caused wildfires the first house destroyed always occurred on the day of ignition. In contrast, the first house destroyed was after the day of ignition for 78% of lightning-
caused wildfires. Lightning-caused wildfires that destroyed houses were significantly larger ($P < 0.001$) in area than human-caused wildfires that destroyed houses. Targeting fire prevention strategies around ignition causes, such as improving powerline safety and arson reduction programmes, and fuel reduction treatments may decrease the number of wildfires that destroy houses.

Over 2200 forest and 4600 grass fires in New South Wales were investigated to determine the dominant influences on the containment of wildfires. A random forest modelling approach was used to analyse the effect of a range of human and environmental factors. The number of suppression resources per area of fire were the dominant influence on the containment of both forest and grass fires. As fire weather conditions worsened the probability of containment decreased across all fires and as fuel loads and slope increased the probability of containment decreased for forest fires. Slope and response time had only a minor influence on the probability of containment of grass fires. Environmental controls limit the effectiveness of wildfire management, however, results suggest investment in suppression resources and strategic fuel management will increase the probability of containment.

A Bayesian Network model was developed to quantify the relative effects of mitigation and response strategies on the likelihood of house loss from forest and grass fires in New South Wales bioregions. Existing datasets and empirical models were used to determine the likelihood of ignition, containment and impact on houses. The relative reduction in risk from investment in arson and powerline ignition prevention strategies, prescribed burning, suppression resources and suppression response time was investigated. Within bioregions, the annual risk of house losses was 3 or 4 times higher for forest fires than grass fires. A 20% increase in tankers per ha of fire, followed by 20% reduction in powerline ignitions produced the greatest reduction in annual house loss risk for both forest and grass fires. Increasing the prescribed burning effort was the least effective treatment for reducing house loss from forest fires. The risk of house losses increased and the effectiveness of mitigation and suppression treatments decreased when the forest fire danger index was $> 50$. Increasing the number of suppression resources available may not be possible or practicable given the financial cost involved in tanker purchase, recruitment and training of firefighters and the extra burden this may place of volunteer firefighters. Investing in preventing powerline ignitions should be considered further as this was the ignition cause with the highest likelihood of house loss for both forest and grass fires.
Findings from this thesis identify several directions for future research on prevention treatments to mitigate wildfire risk. Consistent data collection standards by fire agencies is required to underpin models for analysing wildfire risk and investigate the effectiveness of wildfire prevention treatments. The Bayesian Network could be modified to develop a spatially explicit model and extended to include an economic evaluation of each prevention and suppression strategy and mitigation strategies around houses. Wildfire risk to other assets could also be investigated.
Acknowledgements

I thank my supervisors, Dr Owen Price and A/Prof Trent Penman for their support, guidance and encouragement throughout my PhD journey. Despite always being busy, you made yourselves available for countless discussions about my research and always provided constructive criticism in a positive and optimistic manner, for which I am most grateful.

I thank my university colleagues at the Centre for Environmental Risk Management of Bushfires for their support and encouragement throughout my time at Wollongong. In particular, Prof. Ross Bradstock for allowing me the opportunity to undertake a PhD within the Centre and Michael Bedward for his enduring encouragement and support with R programming.

I thank my fellow post-grad students at the University of Wollongong. It was always a pleasure to walk into the room and work alongside such a group of dedicated students. I would particularly like to thank Robert Sawyer and Heather Simpson for their enthusiasm, encouragement and friendship.

I thank the NSW Rural Fire Service and the Victorian Department of Sustainability and Environment for provision of data on wildfire ignitions.

I thank my manager, Dr Simon Heemstra and colleagues at the NSW Rural Fire Service for their encouragement and backing me to pursue my dream. I am especially grateful that my position was held while I studied full time and then was able to return to work on a part time basis.

Finally, and most importantly, I thank my partner Darren and our children Oscar and Myles for their constant love and understanding. Yes, mum’s a bit crazy spending all those years at university.
Certification

I, Kathryn May Collins, declare that this thesis submitted in fulfilment of the requirements for the conferral of the degree Doctor of Philosophy, from the University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualifications at any other academic institution.

Kathryn May Collins
20 August 2018
STATEMENT OF CANDIDATE CONTRIBUTION

The four data chapters presented in this thesis have either been published (Chapters 2, 3 & 4), or prepared for publication (Chapter 5) in collaboration with my supervisors, Owen Price and Trent Penman. The contribution of each author is as follows:

- Conceived and designed the study: KC, OP, TP
- Compiled the data: KC
- Analysed the data: KC
- Wrote the manuscript: KC
- Finalised the manuscript for submission: KC, OP, TP
- Submitted the manuscript for publication: KC
- Prepared responses to reviewer’s comments: KC
- Finalised reviewer’s comments: KC, OP, TP


Chapter 4: Collins, KM, Price, OF, Penman, TD (2018) Suppression resource decisions are the dominant influence on containment of Australian forest and grass fires. *Journal of Environmental Management* **228**, 373-382. KC 70%, OP 15%, TP 15%

Chapter 5: Collins, KM, Penman, TD, Price, OF Examining the relative effects of mitigation and response strategies to reduce the likelihood of house losses from wildfires. Prepared for publication. KC 70%, OP 10%, TP 20%
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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>Australian Bureau of Statistics</td>
</tr>
<tr>
<td>ACT</td>
<td>Australian Capital Territory</td>
</tr>
<tr>
<td>AIC</td>
<td>Akaike’s information criterion</td>
</tr>
<tr>
<td>AUC</td>
<td>area under the curve</td>
</tr>
<tr>
<td>CFA</td>
<td>Country Fire Authority</td>
</tr>
<tr>
<td>DELWP</td>
<td>Department of Environment, Land, Water and Planning</td>
</tr>
<tr>
<td>DEM</td>
<td>digital elevation model</td>
</tr>
<tr>
<td>FFDI</td>
<td>forest fire danger index</td>
</tr>
<tr>
<td>GPS</td>
<td>global positioning system</td>
</tr>
<tr>
<td>mda</td>
<td>mean decrease in accuracy</td>
</tr>
<tr>
<td>NSW</td>
<td>New South Wales</td>
</tr>
<tr>
<td>RFS</td>
<td>Rural Fire Service</td>
</tr>
<tr>
<td>RFSFIRS</td>
<td>Rural Fire Service fire incident reporting system</td>
</tr>
<tr>
<td>RH</td>
<td>relative humidity</td>
</tr>
<tr>
<td>RVI</td>
<td>relative variable importance</td>
</tr>
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Chapter 1

1 INTRODUCTION

1.1 Wildfire risk

Wildfires can have devastating consequences for people, property and the environment. From 1901-2011, there have been 825 known fatalities and over 11,500 houses destroyed by wildfires in Australia (Blanchi et al. 2010; Blanchi et al. 2014). The 7 February 2009 Black Saturday fires in Victoria impacted on 78 towns and resulted in 173 lives lost, 2,133 houses destroyed and direct economic costs conservatively estimated at $4.4 billion (AUD) (Teague et al. 2010). The January 2003 fires which impacted Canberra burnt over 260,000 ha and resulted in four deaths and an estimated damage of $300 million (AUD) including 501 houses destroyed, another 315 houses damaged and major losses to government infrastructure and facilities (McLeod 2003). Damaging fire events are a worldwide problem (see examples in Table 1.1).

<table>
<thead>
<tr>
<th>Country</th>
<th>Year</th>
<th>Size (ha)</th>
<th>Fatalities</th>
<th>Buildings destroyed</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greece</td>
<td>2007</td>
<td>225000</td>
<td>80</td>
<td>1710</td>
<td>San-Miguel-Ayanz et al. 2013</td>
</tr>
<tr>
<td>Russia</td>
<td>2010</td>
<td>&gt;100</td>
<td>54</td>
<td>many 1000’s</td>
<td>Vasquez 2011</td>
</tr>
<tr>
<td>Chile</td>
<td>2014</td>
<td>&gt;600000</td>
<td>11</td>
<td>&gt;2400</td>
<td>Reszka and Fuentes 2015</td>
</tr>
<tr>
<td>Canada</td>
<td>2016</td>
<td>&gt;590000</td>
<td>10</td>
<td>some towns</td>
<td>Landis et al. 2018</td>
</tr>
<tr>
<td>Chile</td>
<td>2016/17</td>
<td>&gt;280000</td>
<td>109</td>
<td>&gt;9500</td>
<td>Gomez-Gonzalez et al. 2018</td>
</tr>
<tr>
<td>Portugal</td>
<td>2017</td>
<td>&gt;215000</td>
<td>44</td>
<td></td>
<td>Nauslar et al. 2018</td>
</tr>
</tbody>
</table>

Agencies are adopting a risk based framework for fire management for a range of reasons. The reasons include: the significant impacts of wildfires to life, property and the environment, increasing cost of fire suppression activities (Gebert and Black 2012), agency budgetary pressures (Thompson et al. 2013) and increasing public scrutiny both through the media and via judicial inquiries (Teague et al. 2010; Eburn and Dovers 2015). The term fire risk has been used to describe the probability of ignition or fire occurring (e.g. Hardy 2005; Ganteaume et al. 2013) but these approaches have the potential to
overlook high risk areas that have only moderate fire probability but very high fire consequences. Therefore, fire risk is a combination of fire behaviour probabilities, ignition likelihood and fire intensity, and fire effects which may be positive or negative (Finney 2005; Tutsch et al. 2010; Miller and Ager 2013). For the purposes of this thesis, wildfire risk is defined as the likelihood of a wildfire starting, spreading and impacting on assets and the possible consequences of this occurring. The term wildfire also refers to bushfire or unplanned vegetation fire and includes grass, forest and scrub fire. A conceptual model of the wildfire risk process is shown in Figure 1.1. The risk analysis process is a key component of this framework as it will identify the spatial extent of assets at risk, quantify the risk and the capacity to reduce risk in a systematic, consistent and objective manner. Fire managers can then make informed decisions about whether to accept or treat the risk. It can also be used to engage and inform the community about wildfire risk to their assets.

In the emergency management sector, agencies use a risk management framework in the form of ‘PPRR – Prevention, Preparedness, Response and Recovery’ (McLoughlin 1985; Emergency Management Australia 2004). They are:

Prevention: activities that seek to eliminate or reduce the impact of wildfires and/or to reduce the vulnerability of assets to the impacts of wildfires. These include ignition management, fuel management, and land use planning and building design treatments (Fig. 1.1) with example activities shown in Table 1.2.

Preparedness: activities that establish arrangements and plans and provide education and information for the community to respond to wildfires if they occur (Table 1.2).

Response: activities that activate the preparedness arrangements and plans to respond to wildfires. This includes suppression treatments (Fig. 1.1) and other examples shown in Table 1.2.

Recovery: activities that assist the community affected by wildfires (Table 1.2).
Figure 1.1 Conceptual model describing the process for wildfire risk. Black rectangles represent wildfire risk. Circles represent the drivers of fire behaviour. White rectangles represent management treatments.

Table 1.2 Examples of activities used to reduce wildfire risk.

<table>
<thead>
<tr>
<th>Prevention</th>
<th>Preparedness</th>
<th>Response</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignition management</td>
<td>Resource allocation management systems</td>
<td>Firefighting activities (Suppression)</td>
<td>Social and economic welfare</td>
</tr>
<tr>
<td>e.g. fire permits, total</td>
<td>Firefighter training</td>
<td>Public information</td>
<td>Insurance</td>
</tr>
<tr>
<td>fire bans, solid fuel</td>
<td>Pre-incident plans</td>
<td>Warnings</td>
<td>Reconstruction of physical assets</td>
</tr>
<tr>
<td>bans, restricting access,</td>
<td>Fire detection activities</td>
<td>Emergency alerts</td>
<td>Rehabilitation of environmental</td>
</tr>
<tr>
<td>arson prevention schemes</td>
<td>e.g. prescribed burning, mechanical treatments,</td>
<td></td>
<td>assets</td>
</tr>
<tr>
<td></td>
<td>grazing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel management</td>
<td>Fire trail construction &amp; maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e.g. prescribed burning,</td>
<td>Community engagement activities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mechanical treatments,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>grazing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land use planning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e.g. wildfire-prone land</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mapping, land zoning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>measures, building and</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>landscape design</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Inquiries following significant wildfires often recommend increased prevention measures (McLeod 2003; Ellis et al. 2004; Teague et al. 2010). However, what is often lacking when undertaking wildfire risk analysis, is an understanding of the effectiveness of risk treatment strategies and information to better design prevention and response strategies. In the next subsections the four major treatment strategies to mitigate wildfire risk (Fig. 1.1) are reviewed and then the thesis aims and structure is detailed.

1.2 Ignition management
Four factors must combine for fire to occur: biomass production (i.e. fuel load, type and arrangement); its availability to burn (i.e. fuel dryness); fire weather (i.e. temperature, wind speed and relative humidity to support combustion and fire spread); and ignitions (i.e. natural or anthropogenic sources) (Archibald et al. 2009; Bradstock 2010; Parisien et al. 2012). These factors all vary across space and through time and influence the area burnt (Archibald et al. 2009). If one of these factors is not present (hypothetically ‘switched off’) then fire will not occur (Bradstock 2010). Therefore, in areas where the weather conditions are suitable to sustain combustion, management activities which reduce the number of ignitions and/or reduce the fuel load will influence the spatial pattern of burn probabilities and wildfire risk.

Many studies have used historical fire records to investigate the drivers of ignitions (Costafreda-Aumedes et al. 2017). A variety of explanatory variables have been used to explore the spatial patterns of lightning- (Table 1.3) and human-caused ignitions (Table 1.4). It is evident from previous studies that there are regional variations in the spatial pattern of ignitions e.g. elevation can have either a positive or negative influence on lightning-caused ignitions (Table 1.3). There are also regional variations in the relative importance of variables e.g. human factors were the most important variables in the southern California region (Syphard et al. 2008) whereas climatic factors were the most important for both human- and lightning-caused fires in the Chinese boreal forests (Wu et al. 2014). Some factors operate differently depending on the scale of the analysis e.g. distance to roads had a negative influence on human-caused ignitions at a local level (Syphard et al. 2008) but not at the county level (Syphard et al. 2007).
**Table 1.3** List of variables and their influence on the spatial patterns of wildfires caused by lightning.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Influence</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>Positive</td>
<td>Krawchuk <em>et al.</em> 2006; Narayananaraj and Wimberly 2012; Wu <em>et al.</em> 2014</td>
</tr>
<tr>
<td>Elevation</td>
<td>Negative</td>
<td>Vecin-Arias <em>et al.</em> 2016; Nieto <em>et al.</em> 2012</td>
</tr>
<tr>
<td>Topographic position</td>
<td>Ridges and upper slopes more likely than gullies and lower slopes</td>
<td>McRae 1992; Penman <em>et al.</em> 2013b; Liu <em>et al.</em> 2012</td>
</tr>
<tr>
<td>Slope</td>
<td>Positive</td>
<td>Vecin-Arias <em>et al.</em> 2016</td>
</tr>
<tr>
<td>Slope</td>
<td>No relationship</td>
<td>McRae 1992</td>
</tr>
<tr>
<td>Aspect</td>
<td>More likely for areas exposed to the northwest</td>
<td>Nieto <em>et al.</em> 2012</td>
</tr>
<tr>
<td>Fine fuel moisture code</td>
<td>Positive</td>
<td>Krawchuk <em>et al.</em> 2006; Wu <em>et al.</em> 2014</td>
</tr>
<tr>
<td>Precipitation (summer max)</td>
<td>Negative</td>
<td>Narayananaraj and Wimberly 2012</td>
</tr>
<tr>
<td>Temperature (summer max)</td>
<td>Positive</td>
<td>Narayananaraj and Wimberly 2012</td>
</tr>
<tr>
<td>Fire Danger Index</td>
<td>Positive</td>
<td>Penman <em>et al.</em> 2013b</td>
</tr>
<tr>
<td>Annual seasonal severity rating</td>
<td>Increase with increasing seasonal severity rating</td>
<td>Krawchuk <em>et al.</em> 2006</td>
</tr>
<tr>
<td>Vegetation type</td>
<td>More likely to occur in coniferous forests</td>
<td>Krawchuk <em>et al.</em> 2006; Narayananaraj and Wimberly 2012; Vecin-Arias <em>et al.</em> 2016;</td>
</tr>
<tr>
<td>Fuel age</td>
<td>Increase with older fuel ages</td>
<td>Krawchuk <em>et al.</em> 2006; Penman <em>et al.</em> 2013b</td>
</tr>
<tr>
<td>Distance to roads</td>
<td>Positive</td>
<td>Penman <em>et al.</em> 2013b</td>
</tr>
<tr>
<td>Distance to roads</td>
<td>Negative</td>
<td>Narayananaraj and Wimberly 2012</td>
</tr>
<tr>
<td>Distance to wildland urban interface</td>
<td>Positive</td>
<td>Narayananaraj and Wimberly 2012</td>
</tr>
<tr>
<td>Road density</td>
<td>Negative</td>
<td>Narayananaraj and Wimberly 2012</td>
</tr>
<tr>
<td>Housing density</td>
<td>Negative</td>
<td>Penman <em>et al.</em> 2013b</td>
</tr>
</tbody>
</table>
Table 1.4  List of variables and their influence on the spatial patterns of human-caused wildfires.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Influence</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to roads</td>
<td>No relationship</td>
<td>Syphard et al. 2007</td>
</tr>
<tr>
<td>Distance to drainage features</td>
<td>Positive</td>
<td>Penman et al. 2013</td>
</tr>
<tr>
<td>Distance to towns</td>
<td>Negative</td>
<td>Liu et al. 2012; Miranda et al. 2012; Wu et al. 2014</td>
</tr>
<tr>
<td>Distance to wildland urban interface</td>
<td>Negative</td>
<td>Syphard et al. 2008; Narayanaraj and Wimberly 2012</td>
</tr>
<tr>
<td>Distance to nearest house</td>
<td>Negative</td>
<td>Bar Massada et al. 2013</td>
</tr>
<tr>
<td>Distance from railroads</td>
<td>Negative</td>
<td>Miranda et al. 2012</td>
</tr>
<tr>
<td>Road density</td>
<td>Positive</td>
<td>Costa et al. 2011; Narayanaraj and Wimberly 2012</td>
</tr>
<tr>
<td>Road density</td>
<td>No relationship</td>
<td>Syphard et al. 2007</td>
</tr>
<tr>
<td>Population density</td>
<td>Negative</td>
<td>Narayanaraj and Wimberly 2012</td>
</tr>
<tr>
<td>Housing density</td>
<td>Positive</td>
<td>Penman et al. 2013; Bar Massada et al. 2013</td>
</tr>
<tr>
<td>Intermix wildland urban interface</td>
<td>Increase with increasing proportion of intermix WUI</td>
<td>Syphard et al. 2007;</td>
</tr>
<tr>
<td>Land cover</td>
<td>More likely in urban-rural and agricultural areas than forests</td>
<td>Catry et al. 2009</td>
</tr>
<tr>
<td>Elevation</td>
<td>Negative</td>
<td>Narayanaraj and Wimberly 2012</td>
</tr>
<tr>
<td>Elevation</td>
<td>Positive</td>
<td>Catry et al. 2009</td>
</tr>
<tr>
<td>Slope</td>
<td>Negative</td>
<td>Narayanaraj and Wimberly 2012</td>
</tr>
<tr>
<td>Topographic position</td>
<td>More likely in gullies and lower slopes</td>
<td>Liu et al. 2012</td>
</tr>
<tr>
<td>Fuel age</td>
<td>More likely in recently burnt areas</td>
<td>Penman et al. 2013;</td>
</tr>
<tr>
<td>Vegetation type</td>
<td>More likely in deciduous forests</td>
<td>Liu et al. 2012</td>
</tr>
<tr>
<td>Vegetation type</td>
<td>More likely in shrubland</td>
<td>Syphard et al. 2007</td>
</tr>
<tr>
<td>Vegetation type</td>
<td>Negative for brush</td>
<td>Narayanaraj and Wimberly 2012</td>
</tr>
</tbody>
</table>
Understanding the major drivers of ignitions, the nature of their relationship and where fires are most likely to occur in the landscape, are essential to determining where wildfires pose the greatest risk to people and property. Knowledge of where fires are most likely to occur and which ignitions cause the most damage, could improve resource allocation for fire detection and response, and enable fire prevention strategies that reduce the number of ignitions and minimise the spread of fires to be better targeted.

1.3 Fuel Management

Fuel management strategies aim to protect life and property, and maintain ecological processes and biodiversity by decreasing the potential spread of a wildfire and lowering its intensity which will assist fire suppression efforts (Fernandes and Botelho 2003; Penman et al. 2011a). Fuel management strategies can be achieved through a variety of methods such as clearing, grazing, slashing of grassy vegetation, chemical treatment, mechanical treatments of forests and prescribed burning (Luke and McArthur 1978). Some methods are more suitable to small scale applications e.g. clearing, slashing, chemical treatment and others can be applied over a larger landscape e.g. mechanical treatments of forests and prescribed burning. Here, we will concentrate on prescribed burning treatments as it is the fuel management treatment applied most broadly in the Australian landscape.

There have been various studies which have examined the effectiveness of prescribed burning in relation to time since fuel treatment and fire weather conditions. Prescribed burns are most effective at reducing intensity in the first five years post burn (McCarthy and Tolhurst 2001; Fernandes and Botelho 2003; Bradstock et al. 2010; Price and Bradstock 2010, 2012; Tolhurst and McCarthy 2016). The effect may last up to 10 or more years (McCarthy and Tolhurst 2001; McCaw et al. 2012; Tolhurst and McCarthy 2016) but diminishes as fire weather severity increases (Price and Bradstock 2012; Penman et al. 2013c; Tolhurst and McCarthy 2016; Cary et al. 2017). Under adverse fire weather conditions, recently burnt areas may reduce the intensity of fires (Bradstock et al. 2010; McCaw 2013) but it may not be enough to enable safe and effective fire suppression (Price and Bradstock 2012). This is a significant issue as fires pose the greatest risk to human life and property when the weather conditions are extreme (Blanchi et al. 2010; Blanchi et al. 2014). However, extreme weather conditions generally last for periods of less than ten hours (McCaw 2013) therefore fuel reduced areas will be effective
in aiding fire suppression when conditions have abated or while fires are small i.e. still in their build up phase (Tolhurst and McCarthy 2016).

The effectiveness of prescribed burnt areas at reducing the area burnt by unplanned fires varies regionally. A study in south-west Western Australia found a strong inverse relationship between the extent of prescribed burning and unplanned fire (Boer et al. 2009) whereas studies in the Sydney region have shown a limited effect on fire spread and the extent of unplanned fire (Price and Bradstock 2010; Price and Bradstock 2011). The term leverage is used to quantify the extent of reduction in unplanned fire achieved for each unit of planned fire undertaken (Loehle 2004). The main factors which influence leverage are the extent of unplanned fires, treatment level and spatial design (Price 2012). Leverage values from empirical studies in eucalypt forests in southern Australia are 0.33 (Price and Bradstock 2011) and 0.25 (Boer et al. 2009), 1 in savanna in northern Australia (Price et al. 2012b) and zero in southern coastal California (Price et al. 2012a). In an empirical study examining leverage in 30 bioregions in southern Australia, Price et al. (2015b) found that leverage only occurred in four forest-dominated bioregions, where rainfall, fuel load and fire activity is high and fire weather is mild. Low leverage values do not necessarily mean that a prescribed burning programme is not worthwhile, as leverage does not consider the impact of differences in fire severity on natural resource values and biodiversity (McCaw 2013) or impact on assets. Leverage also does not consider economic values, the costs of undertaking a prescribed burning programme may be less than the sum of the costs of suppression of unplanned fires and potential costs of house losses and human lives (Gill et al. 2013).

The location of treated areas within the landscape is important to protect life and assets. Several studies have concluded that fuel management treatments in the interface zone close to houses are more effective at reducing wildfire spread and reducing the intensity of these fires at the interface than landscape treatments (Syphard et al. 2011; Gibbons et al. 2012; Penman et al. 2014a; Scott et al. 2016). However, landscape burns can contribute to reducing wildfire risk by assisting in the containment of fires, particularly if they are located in high ignition areas. Landscape burns may increase the effectiveness of suppression operations (Plucinski 2012) and provide safe control areas for fire containment (Tolhurst and McCarthy 2016). Landscape burns have the potential to protect environmental values if they reduce the severity of wildfire and hence the impacts
on vegetation and soil (Reinhardt *et al.* 2008; McCaw 2013) and increase the patchiness of wildfires which may provide refugia for fire sensitive species (e.g. Robinson *et al.* 2014; Chia *et al.* 2015; Swan *et al.* 2016).

### 1.4 Land use planning and building design

Land use planning and building design can be used to mitigate wildfire risk by preventing houses and other structures from being exposed to wildfire and reducing the vulnerability of structures to radiant heat and ember penetration. Measures to mitigate wildfire risk are incorporated into planning policies and guidelines in many countries (March and Rijal 2015; Galiana-Martin 2017; Kocher and Butsic 2017) although the regulatory framework to make these measures mandatory has not been enacted in all areas (Harris *et al.* 2011; Muller and Schulte 2011). Planning and building design requirements may include features such as having dedicated water supplies for firefighting; adequate buffer zones (defensible space) between buildings and flammable vegetation; building construction standards for walls, windows, roofing and deck materials; adequate access and egress for firefighters and others; and appropriate road infrastructure.

House ignitions are unlikely to occur if flames or embers do not occur within 40 m around a house (Cohen 2000). This area around the house has been called the home ignition zone (Calkin *et al.* 2014) or defensible space if the vegetation has been modified or cleared (Syphard *et al.* 2014). Studies examining destroyed and surviving houses following wildfires have found that houses are more likely to survive a wildfire if defensible space is present (Gibbons *et al.* 2012; Syphard *et al.* 2014) and well spaced retained trees and shrubs pose less risk than the same cover of trees and shrubs in a few clumped patches (Gibbons *et al.* 2018). Defensible space has also been shown to be as important as building construction and design for house survival in wildfires (Syphard *et al.* 2017).

Land use planning and building design measures typically only apply to new subdivisions and for renovation of existing houses (Muller and Schulte 2011; Holland *et al.* 2013). These measures are required to be maintained throughout the life of the development but compliance is not routinely monitored by local governments (Teague *et al.* 2010). Regulatory controls for building in wildfire-prone areas are not retrospective. There is no requirement for existing houses and structures built prior to these regulations coming into force, to comply with planning and building standards. A large number of existing
houses and other structures in wildfire-prone areas do not comply with current building regulations (Penman et al. 2017). Building owners may voluntarily choose to retrofit their houses although the cost of retrofitting houses can range from approximately $8500 to $47000 and is likely to be higher than residents are prepared to pay to reduce their wildfire risk (Penman et al. 2017).

There have been very few studies which assess the effectiveness of building design provisions. Following the Black Saturday fires in Victoria, the Country Fire Authority reviewed house losses of development applications referred to them (Holland et al. 2013). Only 1% of houses (51) within the fire area had been referred to the Country Fire Authority and six of these were destroyed. The Victorian Building Commission also analysed data on 2,131 houses destroyed in the Black Saturday fires, 8% (177) were required to be built to the Australian Standard AS3959 – Construction of Buildings in Bushfire-prone Areas (Standards Australia 2009; Teague et al. 2010). None of the 71 houses destroyed in the Perth Hills fire (6 February 2011) in Western Australia were built to AS3959 standard (Keelty 2011).

1.5 Suppression

Fire suppression activities are undertaken to reduce the area burnt by wildfires and to protect life, property and infrastructure from being impacted by fire. Suppression strategies usually involve deploying resources as fast as possible to contain the fire to the smallest area possible to minimise the damage caused and suppression costs (Parks 1964). Resources may include tankers (firefighting vehicles), their crew (firefighters), aircraft and earth-moving machinery (e.g. bulldozer, grader). Fire suppression can reduce the area burnt by a wildfire (Cumming 2005; DeWilde and Chapin 2006; Martell and Sun 2008) but fires that escape initial attack can incur large suppression costs (Calkin et al. 2005; Gebert and Black 2012).

The probability of wildfire containment is influenced by environmental and human factors. Environmental factors determine the fire’s behaviour (Fig. 1.1), how fast it is spreading, its flame height, intensity and likelihood of spotting (Cruz et al. 2015). The environmental factors that may influence the probability of containment are fuel type (Hirsch et al. 2004; Arienti et al. 2006), fuel load (McCarthy et al. 2012; Plucinski 2012; Beverly 2017), weather conditions (Arienti et al. 2006; Plucinski 2012, 2013; Beverly
Human factors determine resource placement, the number and type of resources to deploy and suppression tactics. These decisions may influence the probability of containment by affecting resource response time (Arienti et al. 2006; Plucinski 2012), fire area when crews arrive at the fireground (Arienti et al. 2006; McCarthy et al. 2012; Plucinski 2012, 2013; Beverly 2017) and crew size (Hirsch et al. 2004; McCarthy et al. 2012).

Fire intensity has a major influence on suppression effectiveness. Fire intensity is the rate of energy release per unit length of fire front and is dependent on the forward rate of spread of the fire and the available fuel load (Byram 1959). Estimates of the threshold for controllable fire intensity vary depending on the suppression technique and fuel type (Hirsch and Martell 1996). The upper limit for direct suppression with hand tools is estimated to be 350-500 kW/m and for ground-based crews around 2000-4000 kW/m (Hirsch and Martell 1996). However, there are no estimates of intensity limits specifically for tankers, which is the primary suppression resource used in Australia. In dry eucalypt forests, firefighters are generally unable to suppress fires with an intensity > 1000 kW/m due to the number of spot fires occurring across the control line (Budd et al. 1997). The upper limit for firebombing aircraft to stop fire progression is around 3000 kW/m (Loane and Gould 1986). Fire intensity also influences fireline construction rate (Hirsch and Martell 1996; Hirsch et al. 2004). For hand crews, fireline construction rates are relatively constant until falling sharply to zero when head fire intensity is above 800 kW/m (Loane and Gould 1986). Ground-based crews follow a similar pattern with a constant rate of fireline construction up to 500 kW/m before falling rapidly to zero at 2000 kW/m (Loane and Gould 1986).

Understanding the factors that influence the probability of containment of wildfires is an important component in the development of models and tools for assessing wildfire risk to assets, however there have been a few studies that have investigated containment success. Models of containment success can be used for testing scenarios on resource location and the number and type of resources to deploy to wildfires. Suppression strategies can be compared against fire prevention strategies to determine the optimum mix of strategies to mitigate wildfire risk.
1.6 Study aims and thesis structure

The overall aim of this thesis is to investigate the effectiveness of fire prevention and response treatments to mitigate wildfire risk. To achieve this aim research was firstly undertaken to investigate the drivers of ignitions and the nature of their relationship to resolve the literature uncertainty for the study area. Research was also undertaken to determine if ignitions are equal or whether some ignition causes pose more risk than others. Suppression effectiveness was investigated to determine the factors that influence the containment of wildfires; and finally the research results were combined to determine the best combination of wildfire prevention and response strategies to mitigate the risk of house losses. Fuel management and particularly, prescribed burning, has been well studied by previous researchers, therefore we have only included prescribed burning in the combined mitigation study. There have been very few studies exploring land use planning and building design measures, however it is difficult to study the effectiveness of these measures given that most houses have not been built to current policy standards.

Chapter 2 examines the spatial patterns of ignitions at a bioregional scale in south-eastern Australia. A combination of social and biophysical variables are used to model the spatial patterns of wildfire ignitions and investigate whether different categories of ignitions respond to difference explanatory variables.

Chapter 3 examines the relationship between wildfire ignition causes and destroyed houses in south-eastern Australia. A dataset of wildfires that destroyed houses is compiled to determine which ignition causes are more likely to result in destroyed houses and whether there are associated weather conditions that increase the probability of a destroyed house.

Chapter 4 examines the dominant influences on the probability of containment of wildfires in New South Wales, Australia. A large dataset of wildfires is investigated to determine the relative importance of environmental and human factors in containing forest and grass fires.

Chapter 5 examines the relative influence of mitigation and response strategies on the likelihood of houses losses from forest and grass fires in New South Wales bioregions. A Bayesian Network model is developed to quantify the relative reduction in annual house
loss risk from investing in arson and powerline ignition prevention strategies, prescribed burning, suppression resources and suppression response time.

Chapter 6 synthesises the findings from Chapters 2 through 5, summarising the advances this thesis makes to further understanding of wildfire risk to house losses and effectiveness of mitigation treatments. This chapter also describes the implications of this research for fire management and discusses several directions for future research.

Aside from Chapters 1 and 6, all chapters of this thesis have prepared as manuscripts. Chapters 2, 3 and 4 have been published and Chapter 5 has been prepared for submission. Thus, some duplication of introductory material and description of the study area occurs throughout the thesis.
2 SPATIAL PATTERNS OF WILDFIRE IGNITIONS IN SOUTH-EASTERN AUSTRALIA.

2.1 Abstract
Wildfires can have devastating effects on life, property and the environment. Official inquiries following major damaging fires often recommend management actions to reduce the risk of future losses from wildfires. Understanding where wildfires are most likely to occur in the landscape is essential to determining where wildfires pose the greatest risk to people and property. We investigated the spatial patterns of wildfire ignitions at a bioregional scale in New South Wales and Victoria using generalised linear models. We used a combination of social and biophysical variables and examined whether different categories of ignitions respond to different explanatory variables. Human-caused ignitions are the dominant source of ignitions for wildfires in south-eastern Australia and our results showed that for such caused ignitions, population density was the most important variable for the spatial pattern of ignitions. In future years, more ignitions are predicted in the coastal and hinterland areas due to population increases and climate change effects.

2.2 Introduction
Wildfires can have significant effects on life, property and the environment. Damaging wildfire events causing major losses of human lives and homes have occurred in Australia (e.g. Doogan 2006; Teague et al. 2010), Russia (Vasquez 2011), Greece (European Commission 2008), the US (Keeley et al. 2009) and other countries. These events are highlighted widely in the media and typically result in official inquiries (e.g. Kanowski et al. 2005; Teague et al. 2010) that often recommend management actions to reduce the risk of future losses from wildfires. Understanding where wildfires are most likely to occur in the landscape is essential to determining where wildfires pose the greatest risk to people and property.

Four factors must combine for fire to occur: biomass growth; its availability to burn; weather to support combustion; and an ignition source (Archibald et al. 2009; Bradstock 2010). These factors all vary across the landscape and through time (Archibald et al. 2009) and govern the number of fires starting on a particular day in a particular region.
The ignition source may be from humans, either by accidental or deliberate action, or natural sources, predominantly by lightning. Both lightning (Podur et al. 2003; Wu et al. 2014) and human-caused ignitions (Penman et al. 2013b; Wu et al. 2014) occur in clusters, although the factors that influence their spatial distribution may vary.

Many studies have combined social and biophysical data with historical fire records to develop an understanding of the spatial patterns of wildfire ignitions. Wildfires caused by lightning strikes have usually been related to biophysical factors such as elevation (e.g. Narayanaraj and Wimberly 2012; Wu et al. 2014), vegetation type (e.g. Krawchuk et al. 2006; Liu et al. 2012) and fuel moisture (e.g. Krawchuk et al. 2006; Reineking et al. 2010; Wu et al. 2014); and geographical factors such as distance to roads (e.g. Gralewicz et al. 2012; Narayanaraj and Wimberly 2012; Penman et al. 2013b) and to settlements (e.g. Gralewicz et al. 2012; Narayanaraj and Wimberly 2012). Human-caused ignitions have been related to a wide range of variables including population density (e.g. Syphard et al. 2007; Costa et al. 2011; Miranda et al. 2012), housing density (e.g. Miranda et al. 2012; Penman et al. 2013b), distance to settlements (e.g. Reineking et al. 2010; Mundo et al. 2013; Wu et al. 2014), distance to roads (Narayanaraj and Wimberly 2012; Bar Massada et al. 2013; Penman et al. 2013b), vegetation type (e.g. Syphard et al. 2008; Liu et al. 2012), elevation (e.g. Narayanaraj and Wimberly 2012; Bar Massada et al. 2013) and weather factors (e.g. Miranda et al. 2012; Penman et al. 2013b; Wu et al. 2014).

The relationship between wildfire ignitions and its influencing factors varies depending on the region and scale of analysis. For example, in some studies distance to roads was negatively associated with lightning-caused fires (Gralewicz et al. 2012; Narayanaraj and Wimberly 2012) whereas others have found a positive relationship (Penman et al. 2013b); although other factors such as the topographic position of the roads may also be influencing these relationships. Distance to roads was a significant factor in modelling human-caused ignitions in the Californian Santa Monica Mountains (Syphard et al. 2008) but was not significant when the analysis was undertaken at the Californian county level (Syphard et al. 2007). There are also regional differences between the relative importance of variables. For example, distance to development and roads were the most important variables for human-caused fires in the Californian Santa Monica Mountains (Syphard et
al. 2008) whereas these variables were of secondary importance to climate variables in the Chinese boreal forests (Wu et al. 2014).

Studies investigating the spatial patterns of wildfire ignitions in southern Australia have generally been restricted to relatively small geographic areas and time periods. For example, Penman et al. (2013b) examined the spatial pattern of arson and lightning ignitions in the Sydney Basin, McRae (1992) investigated lightning ignitions in the Australian Capital Territory (ACT) and McRae (1995) investigated human-caused ignitions in the ACT. Trends in deliberate ignitions, typically over a 5-year period, were examined by Bryant (2008b) in an Australian-wide study. Hence little is known of the regional variation of ignition patterns at a broader scale in southern Australia. In this study, we investigate the spatial patterns of a range of ignition types at a bioregional scale. We have chosen south-eastern Australia as our study area as it includes the two most populous states in Australia, the landscape is particularly prone to fire and has a history of devastating wildfire events that have resulted in large losses of life (Blanchi et al. 2014) and property (Blanchi et al. 2010). We use a combination of social and biophysical variables to model the spatial patterns of wildfire ignitions and whether different categories of ignitions respond to different explanatory variables. From the findings of previous studies we hypothesise that:

1. Human causes will dominate the ignitions, particularly where population density is high.
2. Ignition rates will be closely correlated with population density as the majority of ignitions in these areas are human caused.
3. Regional variation in lightning ignition will relate to topographic and climatic factors.

2.3 Methods

2.3.1 Study Area

The study area (Fig. 2.1) consisted of the states of New South Wales (NSW) and Victoria in south-eastern Australia (the ACT was not included) and contains Australia’s two largest population centres: Sydney and Melbourne. Two-thirds of the population in the study area reside in these two cities. Other high population areas are generally along
coastal and nearby inland areas (Fig. 2.1). Large areas in the northwest are sparsely populated. The area is diverse with 23 bioregions and 144 subregions which are based on common climate, geology, landform, native vegetation and species information (Interim Biogeographic Regionalisation for Australia ver. 6.1; Department of the Environment, http://www.environment.gov.au/topics/land/national-reserve-system/science-maps-and-data/australias-bioregions-ibra/australias). The study area has five global agro-climatic zones (Appendix A Fig. A1) ranging from warm to hot, very dry desert areas in the far north-west, very cold alpine areas in the south-east and warm, wet subtropical areas on the north coast (Hutchinson et al. 2005). The natural vegetation in the study area can be divided into four main groups: forests; woodlands; chenopods; and grasslands (Appendix A Fig. A2). Eucalyptus species are the predominant vegetation in forests and woodlands (Beadle 1981; Keith 2004) with Casuarina, Acacia and Callitris species also dominant in the semiarid woodlands in central and western NSW (Keith 2004). Areas extensively cleared of natural vegetation are used for intensive purposes, agriculture and plantations (Appendix A Fig. A2 and A3).

2.3.2 Data compilation

For the purposes of this study, a wildfire is defined as an unplanned vegetation fire (AFAC 2012b). Wildfire ignition records were obtained for areas managed by the Country Fire Authority (CFA) and the Department of Environment, Land, Water and Planning (DELWP) in Victoria, and the NSW Rural Fire Service (RFS). The CFA is responsible for the management of fires on private land in the outer metropolitan, regional and rural areas of Victoria. The DELWP is responsible for the management of fires on public land in Victoria. The RFS is responsible for the management of fires in ~95% of NSW. Fires that occur on national parks or state forests in NSW may not be included in the RFS data as these fires may have been managed by firefighters from the relevant land management agency. However, if the RFS attended these fires, then an RFS fire record would have been created. As the RFS and CFA respond to a range of fire incidents, only incidents from these agencies that were coded as vegetation fires in accordance with the Australian Incident Reporting Standard (AFAC 2012a) were included in the study. Each wildfire record was assigned to one of four cause types: accidental, deliberate, lightning, and undetermined (Table 2.1). There was insufficient data available to separate the accidental causes into various ignition method categories as some cause codes were not specific enough to allow further classification and some categories had insufficient numbers across subregions to model these categories separately.

<table>
<thead>
<tr>
<th>Cause Type</th>
<th>Examples of fire causes within category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidental</td>
<td>Accidental escapes from prescribed burns, agricultural burns, debris burning, campfires or cooking fires. Fires accidently lit by a cigarette or other smoking material. Fires caused by electrical malfunction, includes power lines and electrical equipment. Fires caused by equipment or machinery use or malfunction includes cutting, welding equipment, cars, trains and farm machinery. Fires caused by the re-kindling of previously extinguished fires. Fires identified as accidental but no further details available</td>
</tr>
<tr>
<td>Deliberate</td>
<td>Fires where there is evidence of deliberately lit fires, including fires lit by juveniles and fires lit without a fire permit i.e. illegal fires. Suspicious fires where circumstances indicate that the fire was likely to be deliberately lit but ignition source may not be identified</td>
</tr>
<tr>
<td>Lightning</td>
<td>Fires which result from a lightning strike</td>
</tr>
<tr>
<td>Undetermined</td>
<td>Fires where the ignition source was identified as miscellaneous or other and no further details were available to assign to another category. Fires where the ignition source was undetermined or unreported</td>
</tr>
</tbody>
</table>
The Victorian data included records for 12 fire years (July-June) between 1997/98 and 2008/09. Each record had a spatial reference of the ignition point that was used to determine the number of ignitions for each fire year within each subregion of the study area. The NSW data were collated from the RFS Fire Incident Reporting System (RFSFIRS) for the 2001/02 to 2008/09 fire years. As there are a large number of wildfires in this database where the ignition cause is unknown, the data were cross-checked and updated with fire cause information from the RFS fire investigation database, which includes fires from 2004 onwards; the RFS incident management system (ICON), which has fire situation reports from 2005 onwards; and the fire history spatial layer. This reduced the unknown cause records from 53 to 43%. Duplicate records and those relating only to prescribed burns were removed. It was not possible to use an earlier time period for the NSW data as RFSFIRS records prior to 2001 are incomplete. The RFSFIRS data did not include a precise spatial reference for the ignition point, so the primary brigade was used to locate ignitions within subregions. Regardless of which brigade attended the wildfire, the primary brigade is defined in RFSFIRS as the brigade area where the wildfire is located. RFS brigade areas vary in size and may be wholly within a subregion or in many subregions. Where this occurred, ignitions were allocated by multiplying the proportion of the brigade within each subregion by the number of ignitions for the brigade for that year.

Data for a range of potential predictors of ignition patterns (Table 2.2) were sourced. The variables selected were chosen for their relevance to wildfire occurrence based on previous studies and data availability. Population data were sourced from the Australian Bureau of Statistics (ABS) 2006 census collection districts (ABS, http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/2033.0.55.0012006?OpenDocument). The population within each subregion was calculated by multiplying the proportion of the census collection district within each subregion by the number of usual residents recorded for that census collection district, accounting for overlaps between census blocks and subregions in the same way as for ignition data in brigade areas. The percentage area of natural vegetation for each subregion was calculated using the 100-m resolution vegetation map (National Vegetation Information System ver. 4.1; Department of the Environment, http://www.environment.gov.au/land/native-vegetation/national-vegetation-information-system/data-products). The mean and standard deviation of elevation of
each subregion was calculated based on a digital elevation model (DEM). For the NSW subregions, a 25-m resolution DEM obtained from the NSW Office of Environment and Heritage was used and a 30-m resolution DEM from Geoscience Australia was used for the Victorian subregions. The average annual lightning ground flash density of each subregion was determined using gridded (0.5 x 0.5°) continental data from the Bureau of Meteorology (http://www.bom.gov.au/jsp/ncc/climate_averages/thunder-lightning/index.jsp?maptype=otdg#maps). Gridded (0.05 x 0.05°) continental climate data were used to determine daily precipitation, maximum temperature, relative humidity (RH) at the time of maximum temperature and mean daily wind speed. Full details of the derivation of the weather data is provided in Bradstock et al. (2014). A range of climate variables to represent likely fire weather was selected as potential predictors of annual ignition density. These were the yearly rainfall for the fire year; the July to December rainfall; the number of ‘hot days’ per fire year, with maximum temperature >35°C; the number of ‘warm days’ per fire year, with maximum temperature >30°C; the number of days with RH <10% per fire year; the number of days with RH <15% per fire year; the number of days with RH <20% per fire year; and the mean daily wind speed from October to March, which is the statutory fire danger period.

2.3.3 Analyses

The spatial pattern of ignitions was explored using generalised linear models with a Gaussian distribution. The response variable was the natural logarithmic transformations of average annual ignition density for the subregion. Separate analyses were undertaken for total ignitions and each of the four ignition types: accidental, deliberate, lightning and undetermined. Prior to the analysis, Pearson correlation was used to test for correlation between predictor variables. Including variables with correlations above 0.6 can result in multicollinearity (Wintle et al. 2005) and therefore such variables should not be included in the model. Several predictor variables were highly correlated (Table 2.3) and thus were not included together in the same model.

Models representing all possible additive combinations of uncorrelated predictor variables, except for lightning ground flash density and population density, were used in the analyses. Lightning ground flash density was only used for the lightning model and population density was not used for the lightning model. Akaike’s Information Criterion
(AIC) was used for model selection, with the best model being the one with the lowest AIC (Akaike 1973). Models with AIC values more than 10 AIC points higher than the best model are considered to have no support (Burnham and Anderson 2002). The best set of models was determined to be those within 10 AIC points of the best model.

Table 2.2 Variables used in the analyses

RH, relative humidity

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignition density</td>
<td>A logarithmic transformation (ln + 1) of the average number of ignitions per subregion area (million ha) for each fire year</td>
</tr>
<tr>
<td>Population density</td>
<td>Logarithmic transformation (ln) of number of usual residents per subregion area (million ha)</td>
</tr>
<tr>
<td>Lightning ground flash density</td>
<td>The average annual number of lightning ground flashes per subregion area (million ha) per year</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>Mean elevation for the subregion (m)</td>
</tr>
<tr>
<td>Elevation standard deviation</td>
<td>Standard deviation of elevation for the subregion (m)</td>
</tr>
<tr>
<td>Natural vegetation</td>
<td>Percentage area of natural vegetation within the subregion</td>
</tr>
<tr>
<td>Number of hot days</td>
<td>Number of hot days in the subregion; i.e. temperature &gt;35°C for each fire year</td>
</tr>
<tr>
<td>Number of warm days</td>
<td>Number of warm days in the subregion; i.e. temperature &gt;30°C for each fire year</td>
</tr>
<tr>
<td>Yearly rainfall</td>
<td>Total rainfall in the subregion for each fire year (mm)</td>
</tr>
<tr>
<td>July-December rainfall</td>
<td>July-December rainfall in the subregion for each fire year (mm)</td>
</tr>
<tr>
<td>Mean daily October-March wind speed</td>
<td>Mean daily October-March wind speed in the subregion for each fire year (m/s)</td>
</tr>
<tr>
<td>Number of days where RH &lt; 10%</td>
<td>Number of days in the subregion where the RH is less than 10% for each fire year</td>
</tr>
<tr>
<td>Number of days where RH &lt; 15%</td>
<td>Number of days in the subregion where the RH is less than 15% for each fire year</td>
</tr>
<tr>
<td>Number of days where RH &lt; 20%</td>
<td>Number of days in the subregion where the RH is less than 20% for each fire year</td>
</tr>
</tbody>
</table>
Table 2.3 Correlations (R-values) between candidate predictor variables for data averaged over all years.

Pairs of variables which were highly correlated (R>0.6) were not included in the same model. RH, relative humidity

<table>
<thead>
<tr>
<th></th>
<th>Population density</th>
<th>Lightning ground flash density</th>
<th>Natural vegetation % cover</th>
<th>Mean Elevation</th>
<th>Elevation standard deviation</th>
<th>Number of days &gt; 35°C</th>
<th>Number of days &gt; 30°C</th>
<th>Yearly rainfall</th>
<th>July-December rainfall</th>
<th>Mean daily wind speed October-March</th>
<th>Number of days RH &lt; 10%</th>
<th>Number of days RH &lt; 15%</th>
<th>Number of days RH &lt; 20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population density</td>
<td>0.27</td>
<td>-0.60</td>
<td>0.06</td>
<td>0.33</td>
<td>-0.69</td>
<td>-0.64</td>
<td>0.55</td>
<td>-0.38</td>
<td>-0.68</td>
<td>-0.72</td>
<td>-0.73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lightning ground flash density</td>
<td>0.27</td>
<td>0.12</td>
<td>0.28</td>
<td>0.47</td>
<td>-0.34</td>
<td>-0.27</td>
<td>0.43</td>
<td>0.32</td>
<td>-0.55</td>
<td>-0.33</td>
<td>-0.38</td>
<td>-0.41</td>
<td></td>
</tr>
<tr>
<td>Natural vegetation % cover</td>
<td>-0.60</td>
<td>0.12</td>
<td>-0.15</td>
<td>-0.02</td>
<td>0.44</td>
<td>0.37</td>
<td>-0.20</td>
<td>-0.27</td>
<td>0.34</td>
<td>0.49</td>
<td>0.51</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>Mean elevation</td>
<td>0.06</td>
<td>0.28</td>
<td>-0.15</td>
<td>0.62</td>
<td>-0.58</td>
<td>-0.60</td>
<td>0.52</td>
<td>0.59</td>
<td>-0.71</td>
<td>-0.40</td>
<td>-0.46</td>
<td>-0.50</td>
<td></td>
</tr>
<tr>
<td>Elevation standard deviation</td>
<td>0.33</td>
<td>0.47</td>
<td>-0.02</td>
<td>0.62</td>
<td>-0.72</td>
<td>-0.72</td>
<td>0.75</td>
<td>0.76</td>
<td>-0.68</td>
<td>-0.51</td>
<td>-0.59</td>
<td>-0.64</td>
<td></td>
</tr>
<tr>
<td>Number of days &gt; 35°C</td>
<td>-0.69</td>
<td>-0.34</td>
<td>0.44</td>
<td>-0.58</td>
<td>-0.72</td>
<td>0.97</td>
<td>-0.83</td>
<td>-0.88</td>
<td>0.66</td>
<td>0.86</td>
<td>0.92</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>Number of days &gt; 30°C</td>
<td>-0.64</td>
<td>-0.27</td>
<td>0.37</td>
<td>-0.60</td>
<td>-0.72</td>
<td>0.97</td>
<td>-0.84</td>
<td>-0.88</td>
<td>0.61</td>
<td>0.76</td>
<td>0.84</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>Yearly rainfall</td>
<td>0.55</td>
<td>0.43</td>
<td>-0.20</td>
<td>0.52</td>
<td>0.75</td>
<td>-0.83</td>
<td>-0.84</td>
<td>0.94</td>
<td>-0.53</td>
<td>-0.65</td>
<td>-0.73</td>
<td>-0.79</td>
<td>-0.79</td>
</tr>
<tr>
<td>July-December rainfall</td>
<td>0.55</td>
<td>0.32</td>
<td>-0.27</td>
<td>0.59</td>
<td>0.76</td>
<td>-0.88</td>
<td>-0.88</td>
<td>0.94</td>
<td>-0.55</td>
<td>-0.71</td>
<td>-0.79</td>
<td>-0.83</td>
<td>-0.83</td>
</tr>
<tr>
<td>Mean daily wind speed October-March</td>
<td>-0.38</td>
<td>0.34</td>
<td>-0.71</td>
<td>-0.68</td>
<td>0.66</td>
<td>0.61</td>
<td>-0.53</td>
<td>-0.55</td>
<td>0.59</td>
<td>0.64</td>
<td>0.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of days RH &lt; 10%</td>
<td>-0.68</td>
<td>-0.33</td>
<td>0.49</td>
<td>-0.40</td>
<td>-0.51</td>
<td>0.86</td>
<td>0.76</td>
<td>-0.65</td>
<td>-0.71</td>
<td>0.59</td>
<td>0.98</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>Number of days RH &lt; 15%</td>
<td>-0.72</td>
<td>-0.38</td>
<td>0.51</td>
<td>-0.46</td>
<td>-0.59</td>
<td>0.92</td>
<td>0.84</td>
<td>-0.73</td>
<td>-0.79</td>
<td>0.64</td>
<td>0.98</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>Number of days RH &lt; 20%</td>
<td>-0.73</td>
<td>-0.41</td>
<td>0.51</td>
<td>-0.50</td>
<td>-0.64</td>
<td>0.96</td>
<td>0.89</td>
<td>-0.79</td>
<td>-0.83</td>
<td>0.66</td>
<td>0.95</td>
<td>0.99</td>
<td></td>
</tr>
</tbody>
</table>
Model averaging was undertaken following the methods described in Burnham and Anderson (2002) and is explained briefly here. For each model in the best set of models, the Akaike weight was calculated. The Akaike weight of a model is the relative likelihood of the model compared with all other models in the set (Burnham and Anderson 2002). The model-averaged coefficient for a particular variable is then calculated by multiplying the model coefficient for that variable by the model Akaike weight and then summing over all models in the set and dividing by the sum of the Akaike weights of all models in the set (Burnham and Anderson 2002). For each variable, its relative variable importance was quantified by summing the Akaike weights for all models containing the variable (Burnham and Anderson 2002). The model fit of the best model was assessed using the explained deviance (Zuur \textit{et al}. 2009).

All analyses were conducted using R statistical package ver. 3.1.0 (R Core Team 2014). The package MuMIn (Barton 2014) was used for model averaging.

\textbf{2.4 Results}
A total of 113 026 ignitions were included in the analysis, 65 643 were in Victoria (Fig. 2.2) and 47 383 in NSW (Fig. 2.3). Accidental ignitions accounted for 33% of the total ignitions; undetermined 31%, deliberate 28% and 9% of the total ignitions were caused by lightning. If only ignitions with a known cause are considered, then 47% are due to accidental causes, 40% due to deliberate actions and 13% to lightning.

Strong spatial patterns of ignition densities existed across the study area, with ignition densities lowest in north-west NSW and generally increasing to the eastern and southern coastal subregions (Figs. 2.4 & 2.5). The highest average annual total ignition density (315 ignitions/1000 km$^2$) was in the west of the Sydney Basin. The lowest average annual total ignition density (0.0003 ignitions/1000 km$^2$) was in the north-west of NSW.
Figure 2.2 Number of ignitions in Victoria by type and fire season.

Figure 2.3 Number of ignitions in New South Wales by type and fire season.
2.4.1 Total ignitions

Sixteen models were included in the best set of models for total ignitions. In the model-averaged model, ignitions increased with population density \((P < 0.001)\) and decreased with the number of warm days \((P = 0.034)\) (Table 2.4). Also included were non-significant positive relationships with yearly rainfall \((P = 0.696)\) and July-December rainfall \((P = 0.882)\), and non-significant negative relationships with mean elevation \((P = 0.111)\), natural vegetation percentage cover \((P = 0.802)\) and October-March wind speed \((P = 0.824)\). Population density was considered the most important variable (relative variable importance RVI = 1) followed by number of warm days (0.84) and mean elevation (0.83). All other variables were considered of low relative importance: natural vegetation percentage cover (0.30), yearly rainfall (0.14), October-March wind speed (0.08) and July-December rainfall (0.02) (Fig. 2.6). The best model explained 89.2% of deviance.

**Figure 2.4** The spatial pattern for all ignition types in relation to subregions.
Figure 2.5 The spatial pattern of accidental, deliberate, lightning & undetermined ignitions in relation to subregion.
Table 2.4  Model-averaged coefficients and standard errors for the spatial pattern of ignitions.
Blank spaces indicates variable not included in model. Significance: values are $P < 0.05$; NS non-significant variable included in the model.

<table>
<thead>
<tr>
<th>Type</th>
<th>Intercept</th>
<th>Population density</th>
<th>Mean elevation</th>
<th>Elevation standard deviation</th>
<th>Natural vegetation % cover</th>
<th>Number of warm days</th>
<th>Yearly rainfall</th>
<th>July-December rainfall</th>
<th>Mean daily wind speed October-March</th>
<th>Number of hot days</th>
<th>Lightning ground flash density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>NS</td>
<td>0.49±0.04</td>
<td>NS</td>
<td>NS</td>
<td>-0.011±0.005</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Accidental</td>
<td>NS</td>
<td>0.39±0.03</td>
<td>-0.0009±0.0002</td>
<td>NS</td>
<td>NS</td>
<td>-0.013±0.0002</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Deliberate</td>
<td>-2.5±0.3</td>
<td>0.50±0.03</td>
<td>-0.0007±0.0002</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.0009±0.0003</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Lightning</td>
<td>3.5±0.23</td>
<td>0.0007±0.0002</td>
<td>-0.010±0.0002</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.001±0.0002</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Undetermined</td>
<td>-2.2±0.3</td>
<td>0.47±0.03</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>0.001±0.0002</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>
2.4.2 Accidental ignitions

Only two models were included in the best set of models for all accidental ignitions. In the model-averaged model, ignitions increased with population density ($P < 0.001$) and decreased with the number of warm days ($P < 0.001$) and mean elevation ($P < 0.001$) (Table 2.4). Also included was a non-significant negative relationship with natural vegetation percentage cover ($P = 0.539$). Population density, mean elevation and number of warm days were considered the most important variables ($RVI = 1$) and natural vegetation percentage cover was considered to have low relative importance (0.45) (Fig. 2.6). The best model explained 88.3% of deviance.

The accidental model includes ignitions from many different ignition methods (Table 2.1) that potentially have contrasting spatial patterns. For example, wildfires ignited by smoking, machinery or equipment use would be expected to occur more near urban areas than wildfires started by campfires. However, there were insufficient data available as some cause codes were not specific enough to allow further classification and some categories had insufficient numbers across subregions to model these categories separately.

2.4.3 Deliberate ignitions

Eight models were included in the best set of models for deliberate ignitions. In the model-averaged model, ignitions increased with population density ($P < 0.001$) and
yearly rainfall \((P = 0.003)\) and decreased with mean elevation \((P < 0.001)\) (Table 2.4). Also included were non-significant positive relationships with natural vegetation percentage cover \((P = 0.781)\), July-December rainfall \((P = 0.931)\) and October-March wind speed \((P = 0.956)\); and non-significant negative relationships with number of warm days \((P = 0.904)\) and elevation standard deviation \((P = 0.959)\). Population density was considered the most important variable \((RVI=1)\) followed by mean elevation \((0.99)\) and yearly rainfall \((0.97)\). All other variables were considered of low relative importance: natural vegetation percentage cover \((0.30)\), number of warm days \((0.02)\), July-December rainfall \((0.01)\), October-March wind speed \((<0.01)\) and elevation standard deviation \((<0.01)\) (Fig. 2.6). The best model explained 83.8% of deviance.

2.4.4 Lightning ignitions

Two models were included in the best set of models for lightning ignitions. In the model-averaged model, ignitions decreased with the number of hot days \((P < 0.001)\), the natural vegetation percentage cover \((P < 0.001)\) and mean elevation \((P = 0.003)\) (Table 2.4). Also included was a non-significant positive relationship with lightning ground flash density \((P = 0.945)\). There was little difference in the RVI (Fig. 2.6), the number of hot days, natural vegetation percentage cover and lightning ground flash density were the most important variables \((RVI = 1)\) and mean elevation marginally lower \((RVI = 0.99)\). The best model explained 67.2% of deviance.

2.4.5 Undetermined ignitions

Six models were included in the best set of models for undetermined ignitions. In the model-averaged model, ignitions increased with population density \((P < 0.001)\) and yearly rainfall \((P < 0.001)\) (Table 2.4). Also included were non-significant negative relationships with mean elevation \((P = 0.184)\), natural vegetation percentage cover \((P = 0.881)\) and October-March wind speed \((P = 0.902)\). Population density and yearly rainfall were considered the most important variables \((RVI = 1)\) followed by mean elevation \((0.77)\). All other variables were considered of low relative importance: natural vegetation percentage cover \((0.29)\) and October-March wind speed \((0.07)\) (Fig. 2.6). The best model explained 84.9% of deviance.
2.5 Discussion

Human-caused ignitions are the dominant source of ignitions for wildfires in south-eastern Australia. Our results indicate that for human-caused ignitions, population density was the most important variable for the spatial pattern of ignitions with more ignitions occurring in areas of higher population density. This result was not surprising given that 87% of ignitions with a known cause in the study area are due to humans, and is consistent with results from an Australia-wide study (Bryant 2008a), and from California (Syphard et al. 2007), Canada (Gralewicz et al. 2012) and south-western Europe (Oliveira et al. 2014).

It is difficult to separate the climate-topography relationship from the patterns of human population. Ignitions increased as rainfall increased or the number of warm days decreased. The highest population densities are in the coastal areas. These areas have a higher rainfall and fewer days each year with a maximum temperature above 30°C than do the sparsely populated western arid and semiarid areas, which have many warm days each year but very few ignitions. Similarly, accidental and deliberate ignitions were more likely to occur on low-elevation areas. This was expected, given that the highest population densities are in the lower elevation coastal areas. Other studies have also found that arsonists are more likely to light fires in easily accessible areas, close to roads and populated areas (Bryant 2008a; Reineking et al. 2010; Penman et al. 2013b; Serra et al. 2014). It is also interesting to note that the model for undetermined ignitions more closely aligns with the model for deliberate ignitions than the accidental model. This suggests that deliberate ignitions are more likely to be the major component of the undetermined ignitions.

Lightning ignition probability increased as the number of hot days decreased, which reflects that fewer lightning ignitions occurred in the western arid and semiarid areas (Fig. 2.5 & Appendix A Fig. A1). The negative relationship between lightning ignitions and mean elevation was not expected as several previous studies reported that lightning-caused fires were more likely to occur in high-elevation areas (Podur et al. 2003; Krawchuk et al. 2006; Penman et al. 2013b; Wu et al. 2014; Yang et al. 2015). It is possible that the coarse spatial resolution used for this study may be masking finer scale relationships such as topographic position (Parisien et al. 2014). Lightning ground flash density was not a good predictor of lightning fire ignitions which highlights that other
factors are also important in determining if a fire occurs from a lightning stroke. A study on lightning-caused wildfires in Victoria by Dowdy and Mills (2012b) found that the average chance of fire per lightning stroke is 0.42%. However, if less than 1 mm of rainfall occurs, the chance of fire per stroke is increased 4-fold (Dowdy and Mills 2012a). Fuel moisture is also an important indicator of a high chance of a wildfire from lightning (Dowdy and Mills 2012a; Liu et al. 2012; Yang et al. 2015).

More ignitions are likely under the climate change predictions for south-eastern Australia. Clarke et al. (2011) predict an increase in temperature and reduced rainfall by 2100 for the eastern and southern regions of the study area. The resultant reduction in fuel moisture will increase fuel ignitability and the proportion of fuel available to burn, particularly in the subregions dominated by forests in the coastal and hinterland areas (Appendix A Fig. A2). However, for the western woodland, chenopod and grassland areas (Appendix A Fig. A2), a warmer climate may not result in more fire ignitions as fire may be more strongly limited by biomass growth than fuel moisture (Bradstock 2010; Bradstock et al. 2014).

Potential increases in ignitions may also result from population increases. Australian population projections forecast that the fastest rates of population growth outside of capital cities will likely occur in the peri-urban and coastal regions (McGuirk and Argent 2011), many of which are located close to natural vegetation. The increase in population adjacent to natural vegetation areas combined with the projected climate change effects is likely to result in more ignitions in these areas, increasing the risk of loss of life and property from wildfires. Urban development patterns therefore need to be managed so that they are not a driver of vulnerability to climate change and fire risk. Development of vacant land surrounded by existing development (infill) and expansion growth along the edge of existing development, is likely to result in lower fire risk than that for isolated development clusters surrounded by undeveloped land (Syphard et al. 2013; Price and Bradstock 2014). Planning policies such as specific siting requirements with regard to proximity to vegetation, defendable space around properties, dedicated water supplies for firefighting and building construction codes in fire-prone areas can also reduce the fire risk of a particular development (NSW Rural Fire Service 2006; Country Fire Authority 2012).
Model results were limited by the quality and coverage of the fire incident records. The quality of the fire incident data vary between and within fire agencies. Only a small portion of the fires were likely to have been subject to a detailed causal investigation. Without a detailed investigation, there is likely to be a greater level of subjectivity in the cause assessment, with the accuracy of the assessment being subject to the experience of the reporting fire officer (Bryant 2008b). There is also variation in how wildfires were reported. In some cases, there has been only one report created for wildfires that were close to each other and have separate ignition points, whereas in other cases these have been recorded as separate wildfires. There may be omissions in the NSW data of wildfires which occurred in or near public forests as the RFS may not have attended these wildfires. It was not possible to combine data from other NSW agencies as individual databases were not compatible, making it impossible to ensure that records were not duplicated.

As the precise point location for all ignitions was not available, it was not possible to define the actual conditions of the ignition location, so predictor variables had to be defined using a coarse scale. Therefore, small-scale spatial variation in predictor variables, particularly topography and vegetation cover may have been masked and not accurately represented. Similarly using average annual climate variables may not have accurately represented the effect of weather on ignitions. For example, 5 consecutive days of temperature above 35°C could potentially result in more ignitions than 5 days spread throughout the year. Similarly, the combined effect of weather elements, for example days of above average temperature and wind speed, may not be well represented in the study.

2.6 Conclusion
The majority of wildfires in south-eastern Australia are due to the action of humans. The spatial pattern of ignitions is largely influenced by people, with more ignitions occurring as the population density increases. In future years, more ignitions are expected in the coastal and hinterland areas due to population increases and climate change effects. Urban expansion development planning should aim to reduce fire risk by minimising new developments surrounded by undeveloped land and including wildfire protection measures in planning policies. Future research should investigate whether there are any links with ignition type and loss by examining wildfires which have caused damage and ignition type, the ignition conditions, timing and location.
Chapter 3

3 SOME WILDFIRE IGNITION CAUSES POSE MORE RISK OF DESTROYING HOUSES THAN OTHERS

3.1 Abstract

Many houses are at risk of being destroyed by wildfires. While previous studies have improved our understanding of how, when and why houses are destroyed by wildfires, little attention has been given to how these fires started. We compiled a dataset of wildfires that destroyed houses in New South Wales and Victoria and, by comparing against wildfires where no houses were destroyed, investigated the relationship between the distribution of ignition causes for wildfires that did and did not destroy houses. Powerlines, lightning and deliberate ignitions are the main causes of wildfires that destroyed houses. Powerlines were 6 times more common in the wildfires that destroyed houses data than in the wildfires where no houses were destroyed data and lightning was 2 times more common. For deliberate- and powerline-caused wildfires, temperature, wind speed, and forest fire danger index were all significantly higher and relative humidity significantly lower ($P < 0.05$) on the day of ignition for wildfires that destroyed houses compared with wildfires where no houses were destroyed. For all powerline-caused wildfires the first house destroyed always occurred on the day of ignition. In contrast, the first house destroyed was after the day of ignition for 78% of lightning-caused wildfires. Lightning-caused wildfires that destroyed houses were significantly larger ($P < 0.001$) in area than human-caused wildfires that destroyed houses. Our results suggest that targeting fire prevention strategies around ignition causes, such as improving powerline safety and targeted arson reduction programmes, and reducing fire spread may decrease the number of wildfires that destroy houses.

3.2 Introduction

Many people live in areas that place them at risk from the devastating impact of wildfires. There are numerous examples globally of wildfires that have caused the loss of life and destruction of many houses (e.g. Filmon 2004; Keeley et al. 2004; Doogan 2006; Keeley et al. 2009; Teague et al. 2010; Vasquez 2011; San-Miguel-Ayanz et al. 2013). These events typically cause major social disruption and may result in billions of dollars of damages. For example, the 2009 Black Saturday fires in Victoria impacted on 78 towns
and resulted in 173 lives lost, 2133 houses destroyed and direct economic costs conservatively estimated at $4.4 billion (Teague et al. 2010). Although relatively few fires cause major losses of human lives and homes (Gill et al. 2013), there is potential for the number of destructive wildfires to increase due to population growth, more homes being built in the wildland urban interface (Hammer et al. 2009; Hughes and Mercer 2009; Mann et al. 2014) and climate change (Hasson et al. 2009; Clarke et al. 2011; Bryant and Westerling 2014).

The probability of a wildfire destroying a house is determined by three elements: the probability of an ignition occurring, the probability of a fire spreading to where a house is located and the probability that a house will be destroyed in that fire (Bradstock and Gill 2001). If an ignition occurs, fire suppression may stop a wildfire from spreading and reaching houses although this is dependent on a number of factors such as weather (Arienti et al. 2006; Plucinski 2012; Morin et al. 2015), fuel type (Arienti et al. 2006), fuel load (McCarthy et al. 2012; Plucinski 2012), slope (McCarthy et al. 2012; Plucinski 2012), response time (Arienti et al. 2006; Plucinski 2012), number of resources available (McCarthy et al. 2012) and the fire size when resources commence suppression activities (Arienti et al. 2006; Plucinski 2012; Morin et al. 2015). If fire spreads to where houses are located, the probability of a house being destroyed depends on the level of fire exposure (radiant heat, flame contact and ember density) (Wilson and Ferguson 1986; Cohen 2000), the vulnerability (construction, design, material and siting) of the house (Wilson and Ferguson 1986; Cohen 2000; Mell et al. 2010) and suppression actions of fire agencies or residents (Wilson and Ferguson 1986; Ramsay et al. 1996; Whittaker et al. 2013).

Fire weather is the dominant factor that determines the probability of wildfire destroying a house (Gibbons et al. 2012; Price and Bradstock 2012; Penman et al. 2014a; Penman et al. 2014b). Fire weather has a major influence on ignition probability (Penman et al. 2013b), fire spread, ember spotting distance and fire intensity (McArthur 1967; Luke and McArthur 1978) which in turn determines the probability of fire suppression success (Luke and McArthur 1978; Hirsch and Martell 1996; Gill 2005). Most houses destroyed by wildfires occur during periods of extreme fire weather (Cunningham 1984; Blanchi et al. 2010; Syphard et al. 2012) when opportunities for safe and effective fire suppression actions are very restricted (Plucinski 2012; Penman et al. 2013c). Under these weather
conditions, the effectiveness of fuel reduction treatments is also limited (Moritz et al. 2004; Syphard et al. 2011; Price and Bradstock 2012; Penman et al. 2013c) but house survival is more likely if the treatments are located in areas adjacent to houses than distant landscape treatments (Cary et al. 2009; Bradstock et al. 2012; Gibbons et al. 2012; Penman et al. 2014a; Penman et al. 2014b; Syphard et al. 2014).

Wildfire ignitions are either due to human, through accidental or deliberate action, or natural sources. The spatial and temporal pattern of ignitions are associated with complex drivers that vary with different ignition causes (e.g. Miranda et al. 2012; Penman et al. 2013b; Syphard and Keeley 2015). Many human-caused ignitions occur close to roads (Penman et al. 2013b; Syphard and Keeley 2015) and populated areas (Syphard and Keeley 2015) whereas lightning ignitions are more likely to occur away from the wildland urban interface in low population density areas (Narayanaraj and Wimberly 2012; Penman et al. 2013b). Ignition location influences the probability of a wildfire impacting on houses. The closer the ignition is to houses, the more likely it will spread to a house under any weather conditions (Price and Bradstock 2013). Under extreme weather conditions, wildfires starting long distances from the wildland urban interface may reach houses (Price and Bradstock 2013; Penman et al. 2014a).

An understanding of which ignition causes result in destroyed houses can provide a valuable insight into identifying potential management strategies to reduce the number of wildfires that destroy houses. As far as we can ascertain, there have been no previous studies comparing the role of ignition cause on destroyed houses. Previous simulation studies have suggested that an increase in ignition management effort, simulated by a reduction in ignition probabilities, can be more effective than fuel management in reducing area burned adjacent to assets (Cary et al. 2009).

In this study, we investigated the relationship between wildfire ignition causes and destroyed houses in south-eastern Australia. We compiled a dataset of wildfires that destroyed houses to determine which ignition causes are more likely to result in destroyed houses and whether there are associated weather conditions that increase the probability of a destroyed house.
3.3 Methods

The study area (Fig. 3.1) was defined by the boundaries of the states of New South Wales and Victoria. These states have the highest number of wildfires that destroyed houses in Australia (Blanchi et al. 2010). Housing density is highest in Sydney and Melbourne, where two thirds of the population in the study area reside (Fig. 3.1). Other high housing density areas are in coastal areas and a few inland cities. The major vegetation in the coastal and mountainous hinterland areas are *Eucalyptus* species dominated forests and woodlands (Beadle 1981; Keith 2004). These forests can burn at very high intensities (> 50,000 kW/m) but usually with low frequency (20-100 year) (Murphy et al. 2013). Similarly the mallee eucalypts in north-western Victoria and south-western New South Wales can burn at high intensities (10,000 – 50,000 kW/m) also with low frequency (20-100 year) (Murphy et al. 2013). Most of the other areas are either pasture, croplands or shrublands that burn at lower intensities (< 5,000 kW/m) with frequency intervals between 5-100 years (Murphy et al. 2013).

![Figure 3.1](image)

**Figure 3.1** Location of study area and housing density, housing units/km² in relation to local government areas. Source: generated from data from the Australian Bureau of Statistics 2011 Census of Population and Housing. Developed using Administrative Boundaries produced by PSMA Australia Limited licensed by the Commonwealth of Australia under Creative Commons Attribution 4.0 International licence (CC BY 4.0).
3.3.1 Long term destroyed house data

A dataset of wildfires that destroyed houses was developed by collating available data on such wildfires from July 1951 to June 2015 and their ignition cause. Although houses were destroyed by wildfire in the study area prior to 1951, most notably in 1926, 1939 and 1944 when over 500 houses were destroyed by wildfires each year (Blanchi et al. 2014), the available data on these wildfires was not of sufficient detail to be included. Only wildfires that destroyed a house were included in the dataset. Wildfires that only damaged houses or destroyed other buildings or property such as sheds, business premises, caravans and cars were not included in the dataset as information on these wildfires was not consistently available.

A range of information about each wildfire that destroyed a house was captured: fire name or locality, fire start date, likely date the first house was destroyed, location, number of houses destroyed, ignition cause, fire size, and fuel type. The location was recorded as the local government area where the house was destroyed as this was the finest scale the destroyed house data could be attributed to with reasonable precision. The fire size was recorded as the total number of hectares burnt by the wildfire. If multiple wildfires with the same ignition cause merged then this was recorded as a single wildfire for this cause. If fires with different ignition causes merged, then the total fire size was allocated on an equal basis for each ignition cause. Where possible, the fuel type the fire burnt through was recorded to provide an indication of fire behaviour. (A redacted dataset (excludes fire name, locality and fire start date) is provided in Appendix B Table B1).

A number of different data sources were accessed in order to compile the destroyed houses dataset. These included fire agency databases, annual reports and media releases, coronial inquest reports, royal commission reports, post fire review reports, Victorian municipal fire management plans, journal articles, books and newspaper articles. The details of the sources of information are provided in Appendix B Table B2. There may be additional wildfires where houses were destroyed within the study period (1951-2015) but there was insufficient information to include them in the dataset.
3.3.2 12 Year comparative data

To enable a comparison of wildfires that destroyed houses and those that did not (i.e. wildfires where no houses were destroyed), wildfire ignition records were obtained from the Country Fire Authority and the Department of Environment, Land, Water and Planning in Victoria and the New South Wales Rural Fire Service. The ignition cause and date of ignition were used in the analysis. The Victorian wildfires where no houses were destroyed data included records for 12 fire years (July to June) between 1997/98 and 2008/09 and were compared against wildfires that destroyed houses in Victoria from 1997/98 to 2008/09. The New South Wales wildfires where no houses were destroyed data included records for 12 fire years between 2001/02 and 2012/13 and were compared against wildfires that destroyed houses in New South Wales from 2001/02 to 2012/13. Only wildfires that destroyed houses within the relevant 12 year period were used in the comparative analysis as the distribution of ignitions is unlikely to be same across all years of the 64 year destroyed house dataset.

Weather records from the nearest available Bureau of Meteorology station were sourced for the 12 year comparative analysis for both wildfires that did and did not destroy houses. For the day of ignition we extracted the 1500h temperature, relative humidity (RH), wind speed and calculated the forest fire danger index (FFDI). The FFDI is related to the chance of a fire igniting, its rate of spread and difficulty of suppression (Noble et al. 1980) and has been used to examine the risk of wildfires destroying houses (Bradstock and Gill 2001; Blanchi et al. 2010). For most of the wildfires, the time of ignition was not known, so the 1500h weather was chosen as this is usually when the maximum FFDI is likely to occur (Long 2006).

Ignitions with known causes were grouped into four causal categories: deliberate, lightning, powerlines and other known (Table 3.1). Arson and suspicious causes were combined because wildfires that destroy houses usually undergo a detailed causal investigation that may result in more ignitions designated as arson than suspicious. The other known category could not be split any further due to the low numbers of wildfires that destroyed houses for the separate causes within the 12 year comparative period.
### Table 3.1 Description of cause categories used for wildfire ignitions in the 12 year period.

<table>
<thead>
<tr>
<th>Cause</th>
<th>Examples of fire causes within category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deliberate</td>
<td>Fires where there is evidence of deliberately ignited fires, including fires ignited by juveniles and fires ignited without a fire permit i.e. illegal fires</td>
</tr>
<tr>
<td></td>
<td>Suspicious fires where circumstances indicate that the fire was likely to be deliberately ignited but ignition source may not be identified</td>
</tr>
<tr>
<td>Lightning</td>
<td>Fires that result from a lightning strike</td>
</tr>
<tr>
<td>Powerlines</td>
<td>Fires caused by powerlines clashing, arcing or a branch or animal contacting live parts of the network or breakage of wires, poles, cross-arms, insulators or other components</td>
</tr>
<tr>
<td>Other known</td>
<td>Fires caused by equipment or machinery use or malfunction. Accidental escapes from prescribed burns, agricultural burns, debris burning, campfires or cooking fires. Fires accidently ignited by a cigarette or other smoking material. Fires accidently caused by ordnance training activities. Fires identified as accidental but no further details available</td>
</tr>
</tbody>
</table>

### 3.3.3 Analysis

#### 3.3.3.1 Long term destroyed house data

Fire sizes of lightning-caused wildfires that destroyed houses were compared to human-caused wildfires that destroyed houses using Welch’s anova. This test was chosen as the results of Bartlett’s test revealed that the data were heteroscedastic. Prior to analysis, the fire size data were checked for normality using histograms and, as the data were highly skewed, it was transformed using natural logarithms.

#### 3.3.3.2 12 Year comparative data

The 12 year data of wildfires that destroyed houses and wildfires where no houses were destroyed were compared graphically by ignition cause (all causes included undetermined ignitions; deliberate, lightning, powerlines and other known) and fire weather element on the day of ignition (FFDI, temperature, wind speed and RH). The cumulative % distribution for wildfires that did and did not destroy houses in the 12 year period for each ignition cause and fire weather element was calculated. Welch’s anova was used to determine if there was a statistically significant difference between the wildfires that destroyed houses and wildfires where no houses were destroyed for each ignition cause and fire weather element. Each of the 4 known ignition causes were tested separately for each fire weather element. For example, temperature on day of ignition for powerline-caused wildfires that destroyed houses were compared to the temperature on day of ignition for the powerline-caused wildfires where no houses were destroyed. Prior to
analysis, each set of data were checked for normality using histograms and a natural logarithmic transformation was applied to the FFDI data. As Bartlett tests showed that for some data the variances were not equal, Welch’s anova was chosen to compare the data. The Fisher’s exact test of independence was used to examine whether the proportion of each of the known ignition cause categories are different when compared between the wildfires that destroyed houses and wildfires where no houses were destroyed for the 12 year period. The tests were conducted using R statistical package v3.1.0 (R Core Team 2014).

### 3.4 Results

#### 3.4.1 Long term destroyed house data

From July 1951 to June 2015 there were 250 wildfires that destroyed houses, 155 where the ignition cause was identified and 95 where the cause was undetermined (Table 3.2). There were 7430 houses destroyed by wildfires in the 64 year study period (Table 3.2), with over 85% of these houses destroyed in forest fires. A third of the houses destroyed were the result of wildfires started by powerlines, 25% from fires with an undetermined cause, 22% from deliberately ignited fires and 11% from fires started by lightning strikes. The main ignition causes in the other known category were equipment / machinery use (14 wildfires, 250 houses destroyed), escapes from fuel reduction burning and agricultural burning activities (13 wildfires, 279 houses destroyed) and wildfires accidently ignited by a cigarette or other smoking material (5 wildfires, 33 houses destroyed).

<table>
<thead>
<tr>
<th>Ignition cause</th>
<th>No. of wildfires that destroyed houses</th>
<th>No. of houses destroyed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deliberate</td>
<td>61</td>
<td>1663</td>
</tr>
<tr>
<td>Powerlines</td>
<td>30</td>
<td>2513</td>
</tr>
<tr>
<td>Lightning</td>
<td>29</td>
<td>843</td>
</tr>
<tr>
<td>Other known</td>
<td>35</td>
<td>580</td>
</tr>
<tr>
<td>Undetermined</td>
<td>95</td>
<td>1831</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>250</strong></td>
<td><strong>7430</strong></td>
</tr>
</tbody>
</table>

The Blue Mountains local government area, located approximately 50 km west of Sydney, had the highest number of wildfires that destroyed houses for a local government area with 15 wildfires (Fig. 3.2). The Surf Coast local government area, located
approximately 120 km southwest of Melbourne, had the highest number of houses destroyed for a local government area with 733 (Fig. 3.3); almost all (730) were destroyed in a wildfire in 1983. Wildfires that destroy a very large number of houses in a single event are infrequent, only 6 wildfires destroyed > 200 houses. These 6 wildfires account for 48% of the total number of houses destroyed by wildfire. Over 60% of wildfires had < 10 houses destroyed in the event.

**Figure 3.2** The number of wildfires that destroyed houses from 1951 to 2015 by local government area. Developed using Administrative Boundaries produced by PSMA Australia Limited licensed by the Commonwealth of Australia under Creative Commons Attribution 4.0 International licence (CC BY 4.0).

The area burnt by a wildfire that destroyed houses ranged from 2 ha to 1.15 million ha (Table 3.3). Lightning-caused wildfires that destroyed houses were significantly larger ($P < 0.001$) in area than human-caused wildfires: median value for lightning-caused ignitions was 26314 ha compared with 3222 ha for human-caused wildfires that destroyed houses.
Figure 3.3 The number of houses destroyed by wildfires from 1951 to 2015 by local government area. Developed using Administrative Boundaries produced by PSMA Australia Limited licensed by the Commonwealth of Australia under Creative Commons Attribution 4.0 International licence (CC BY 4.0).

The first house destroyed most often occurred on the day the wildfire started (Table 3.4). For wildfires started by powerlines, the first house destroyed always occurred on the day the fire started. In contrast, only 6 of 27 lightning-caused wildfires incurred a house destroyed on the day of ignition. For 10 wildfires (5 lightning-caused), it was at least 2 weeks after the fire initially started until the first house was destroyed.
Table 3.3 The number of wildfires that destroyed houses from 1951 to 2015 classified by ignition cause and fire size (ha).

<table>
<thead>
<tr>
<th>Ignition cause</th>
<th>&lt; 100</th>
<th>100 - 999</th>
<th>1000 - 4999</th>
<th>5000 - 9999</th>
<th>10000 - 49999</th>
<th>50000 - 100000</th>
<th>&gt; 100000</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deliberate</td>
<td>4</td>
<td>12</td>
<td>18</td>
<td>10</td>
<td>9</td>
<td>5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Powerlines</td>
<td>2</td>
<td>6</td>
<td>8</td>
<td>1</td>
<td>12</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lightning</td>
<td></td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>7</td>
<td>4</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Other known</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>7</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Undetermined</td>
<td>5</td>
<td>8</td>
<td>9</td>
<td>8</td>
<td>20</td>
<td>3</td>
<td>4</td>
<td>38</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>17</td>
<td>34</td>
<td>43</td>
<td>28</td>
<td>55</td>
<td>16</td>
<td>16</td>
<td>41</td>
</tr>
</tbody>
</table>

Table 3.4 The number of wildfires that destroyed houses from 1951 to 2015 classified by ignition cause and the number of days from fire ignition until the first house was destroyed.

<table>
<thead>
<tr>
<th>Ignition cause</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>&gt; 5</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deliberate</td>
<td>50</td>
<td>4</td>
<td>1</td>
<td></td>
<td></td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Powerlines</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lightning</td>
<td>6</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Other known</td>
<td>21</td>
<td>3</td>
<td>5</td>
<td></td>
<td></td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Undetermined</td>
<td>36</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>143</td>
<td>14</td>
<td>11</td>
<td>4</td>
<td>4</td>
<td>17</td>
<td>57</td>
</tr>
</tbody>
</table>
3.4.2 12 Year comparative study

For deliberate- and powerline-caused wildfires, temperature, wind speed, and FFDI were all significantly higher and RH significantly lower ($P < 0.05$) on the day of ignition for wildfires that destroyed houses compared with wildfires where no houses were destroyed in the same 12 year period (Fig. 3.4). Lightning-caused ignitions had significantly higher wind speed ($P < 0.05$) for wildfires that destroyed houses but FFDI ($P = 0.07$), RH ($P = 0.40$) and temperature ($P = 0.71$) were not significantly different from wildfires where no houses were destroyed in the 12 year period. However, the first house was destroyed on the day of ignition for only 3 of the 18 lightning-caused wildfires in the 12 year period. The other known-caused ignitions had significantly lower RH ($P = 0.05$) for wildfires that destroyed houses but FFDI ($P = 0.10$), temperature ($P = 0.10$) and wind speed ($P = 0.20$) were not significantly different from wildfires where no houses were destroyed in the 12 year period. Most deliberate-caused wildfires that destroyed houses started when the temperature $> 30^\circ$C, wind speed $> 20$ km/hr, RH $< 25\%$ and FFDI $> 25$ (Fig. 3.5). Most powerline-caused wildfires that destroyed houses occurred when the temperature $> 25^\circ$C, wind speed $> 30$ km/hr, RH $< 25\%$ and FFDI $> 30$ (Fig. 3.5).

Wildfires that destroy houses are rare events with only 0.06% of wildfires resulting in a house destroyed in the 12 year comparative period. For the 12 year period, there was a significant difference in the proportion of known ignition causes for wildfires that destroyed houses ($P < 0.001$) when compared with wildfires where no houses were destroyed. Powerlines were 6 times more common in the wildfires that destroyed houses data than in the wildfires where no houses were destroyed data and lightning 2 times more common (Fig. 3.6). The proportion of deliberate ignitions was slightly higher for wildfires that destroyed houses and other known ignitions were 3 times lower in the wildfires that destroyed houses data than the wildfires where no houses were destroyed data.
Figure 3.4 Box plots for ignition causes of wildfires that destroyed houses and wildfires where no houses were destroyed for the 12 years with complementary data for fire weather elements. Forest Fire Danger Index (FFDI), hd = wildfires that destroyed houses, nhd = wildfires where no houses were destroyed, All = all ignition causes including undetermined ignitions.
Figure 3.5 Cumulative % distribution of wildfires that destroyed houses and wildfires where no houses were destroyed by ignition cause for the 12 years with complementary data for fire weather elements. Forest Fire Danger Index (FFDI), dotted line = wildfires that destroyed houses, solid lines = wildfires where no houses were destroyed, All = all ignition causes including undetermined ignitions.
Figure 3.6 The proportion of wildfires that destroyed houses (n=58) and wildfires where no houses were destroyed (n=87055) by known cause for the 12 years with complementary data.

3.5 Discussion

We found that powerlines, lightning strikes and deliberate ignitions are the main ignition causes of wildfires that destroyed houses (Table 3.2). Arson and powerlines are also among the main ignition causes of wildfires that destroyed houses in California (Cal Fire 2016). For deliberate- and powerline-caused wildfires, the fire weather was significantly worse on the day of ignition for wildfires that destroyed houses compared with wildfires where houses were not destroyed (Fig. 3.5). For deliberate ignitions, the first house destroyed most often occurred on the day of ignition whereas for powerline-caused wildfires the first house destroyed always occurred on the day of ignition (Table 3.4), this has not been previously reported in other studies. Our results are consistent with previous research that showed that weather and the proximity of ignition to houses are important factors in determining the probability of houses destroyed by wildfires (Penman et al. 2013c; Price and Bradstock 2013). However, for lightning-caused wildfires proximity of ignition to houses may be less important as the first house destroyed from a lightning-caused wildfire most often occurred at least two days after the fire started (Table 3.4). For these events, weather on subsequent days after ignition is likely to be important, although houses destroyed from grass fires started by lightning strikes usually occurred within a day of the fire starting.
The proportion of deliberately ignited wildfires that destroyed houses is similar to the proportion of deliberately ignited wildfires where no houses were destroyed but powerline- and lightning-caused fires are disproportionately higher for wildfires that destroyed houses (Fig. 3.6). While there are no similar studies investigating ignition causes and destroyed houses, the proportion of powerline-caused wildfires substantially increases in Southern California under high wind conditions and several large destructive wildfires in October 2007 were ignited by powerlines (Mitchell 2013). These results suggest that to decrease the number of wildfires that destroy houses, efforts should be focussed on improving the safety of powerlines, reducing the fire spread of lightning-caused wildfires and reducing the number of deliberate wildfire ignitions.

Powerline-caused ignitions were the most over-represented cause in the wildfires that destroyed houses data and resulted in the most houses destroyed. It has long been recognised that powerlines are a potential source of destructive wildfires and require actions to reduce the risk of ignitions. Inquiries following destructive wildfires in Victoria, recommended improving inspection and maintenance of powerlines and the surrounding vegetation (Barber 1977; Teague et al. 2010), improving safety equipment on networks, for example fitting spreaders to stop conductors from clashing (Barber 1977; Teague et al. 2010), installing devices that automatically switch off power when a fault occurs and changing settings on high fire risk days to reduce energy release if a fault occurs (Teague et al. 2010) and burying cables underground in high risk areas (Barber 1977; Miller et al. 1984; Teague et al. 2010). Following the Black Saturday fires, the Victorian government allocated $750 million to reduce the risk of powerlines causing wildfires, including $200 million to replace network and private powerlines in the highest risk wildfire areas and $500 million to electricity network operators to install new technologies that will better control the faults that may cause fires (Victorian Department of Economic Development Jobs Transport and Resources 2016). Additionally, regulations have been strengthened with major network operators required to prepare a bushfire mitigation plan that details how the network operator will minimise the risk of fire ignition from its supply network and report annually of its performance to an independent regulator. The plans are independently audited and the regulator can direct network operators to implement or modify their plans. If private powerlines are not maintained, then there are provisions to enable network operators to enter the land and
undertake the work. For example, in Victoria, the *Electricity Safety Act 1998* and *Electricity Safety (Bushfire Mitigation) Regulations 2013* detail the plan requirements and schedules for inspecting, testing, maintaining and upgrading network assets. The *Electricity Safety (Electric Line Clearance) Regulations 2015* mandates the minimum vegetation clearance distances for overhead powerlines in Victoria and requires network operators to submit an annual plan for vegetation clearance for approval. Similarly, Californian regulations were strengthened after destructive wildfires caused by powerlines in Southern California in 2007 (California Public Utilities Commission 2012, 2014).

Destroyed houses from powerline-caused wildfires may be largely prevented if the power is temporarily shut off on high fire risk days. There are legislative arrangements that provide for this but they are considered a last resort option as the potential impact on the community may outweigh the risk of leaving the power in service (Barber 1977; Powerline Bushfire Safety Taskforce 2011; California Public Utilities Commission 2012). Temporarily shutting off the power on high fire risk days will also impact on communication networks important for issuing fire warnings to the community, may disrupt water supply and adversely affect the welfare of vulnerable community members. Alternatively, burying cables underground will also eliminate the fire risk but this is expensive e.g. $40 billion for rural areas in Victoria (Powerline Bushfire Safety Taskforce 2011). To date, other measures have been preferred, but it is not yet known whether investing in new technologies, upgrading networks and adopting stricter standards on the design, inspection and maintenance of networks will substantially reduce the potential for powerline-caused destructive wildfires. However, if powerlines are found to be the ignition source of a destructive wildfire, then it is highly likely that network operators will face substantial claims for damages and compensation. Litigation following the Black Saturday fires has seen electricity network operators required to pay over $700 million in damages to people who suffered losses in the fires (*Thomas v. Powercor Australia Ltd* (2011); *Mercirca & Anor v. SPI Electricity Pty Ltd & Ors* (2012); *Matthews v. AusNet Electricity Services Pty Ltd & Ors.* (2014); *Rowe v. AusNet Electricity Services Pty Ltd & Ors.* (2015)).

Lightning-caused wildfires that destroyed houses were found to be significantly larger in size than human-caused wildfires that destroyed houses. This result can be explained by
the spatial patterns of ignitions as lightning ignitions typically occur further away from houses than human-caused ignitions (Gralewicz et al. 2012; Narayanaraj and Wimberly 2012; Penman et al. 2013b) and take longer to reach houses. Their remoteness from populated places may limit fire suppression efforts due to lengthy response times for resources to reach the wildfire. Prevention of lightning is of course impossible but fuel reduction treatments may reduce fires spreading from lightning strikes (Boer et al. 2009; Penman et al. 2013c) and improve the probability of successful fire control (Plucinski 2012). These treatments are most effective if a wildfire encounters them within 5 years of treatment (Bradstock et al. 2010; Price and Bradstock 2010) but under adverse fire weather conditions the fire intensity may still be too high for safe and effective fire suppression (Price and Bradstock 2012) and most houses are destroyed when the FFDI > 50 (Blanchi et al. 2010). Landscape fuel reduction treatments where lightning occurs may be ineffective in limiting the fire spread toward the interface as the level of treatment required to substantially alter the risk of wildfires destroying houses is very large (Bradstock et al. 2012).

Deliberate ignitions typically occur in easily accessible areas, close to urban centres (Penman et al. 2013b; Serra et al. 2014; Syphard and Keeley 2015). Unlike other ignition causes, the arsonist chooses the timing and location. When these ignitions result in destructive consequences pressure is often placed on governments, land managers, fire and law enforcement agencies to reduce arson ignitions (Willis 2005). In response, severe penalty provisions for arson offences have been enacted in Australian, United States and Mediterranean jurisdictions although there is no clear evidence to suggest that this deters arsonists (Willis 2005; Lansdell et al. 2011). However, the fear of being caught may deter arsonists (Mees 1991) and a recent study has shown increasing the number of law enforcement officers led to a decrease in deliberately ignited fires (Abt et al. 2015). Preventing deliberate ignitions is difficult as there will always be some people who choose to light wildfires (Willis 2005) and arsonists are rarely caught (Muller 2009; Lansdell et al. 2011). There is limited knowledge on why and how often people light fires (Ducat and Ogloff 2011); what is known is based on those who have been caught and may not be representative of the those who avoid apprehension (Willis 2005; Ducat and Ogloff 2011). As a consequence, reducing deliberate wildfire ignitions is likely to be more successful if strategies are concentrated on where fires are ignited (arson hot-spots) rather
than the profile of an arsonist (Muller 2009). Potential prevention strategies for arson hot-spots include: community education and arson awareness programmes; reducing fuels in the area; limiting access and increasing patrols of these areas on days of very high fire danger (Muller 2009). It is difficult to evaluate how effective these strategies are as changes in the number of ignitions need to be considered in the context of variations in fire weather and fuel availability over time. However, a Western Australia study has correlated the reduction in the number of deliberate ignitions (Plucinski 2014) to a targeted arson reduction programme in the area (Smith 2004).

Many of the other known ignitions occur due to the careless use of fire or equipment/machinery. Laws have been enacted to reduce these types of ignitions, by restricting when and how activities that may cause wildfires are conducted. For example, machinery such as tractors and harvesters must be fitted with a spark arrester and carry fire suppression equipment. Permits are required to light a fire, except for a cooking fire, in the open during the fire danger period. The fire danger period is typically declared for several months at the onset of warmer weather and when the vegetation becomes drier. A total fire ban may be declared (usually for a 24 h period) when predicted fire behaviour indicates wildfires are likely to spread rapidly and be difficult to control (typically when the FFDI > 50). A total fire ban prohibits the lighting of fires in the open and the use of hot works equipment, such as welding or grinding. These laws will only be effective if people know and understand them. Investigations following an equipment-caused wildfire that destroyed houses in Western Australia found 33% of people interviewed were not aware that a total fire ban had been declared (Heath et al. 2011) and there was a lack of understanding of what activities were prohibited (Keelty 2011).

Our study was limited because 38% of wildfires that destroyed houses the ignition cause was undetermined. In recent years, improvements in fire agency record keeping, the availability of fire investigation specialists and technology such as lightning strike detection systems, has resulted in increased reliability and quality of data on ignition causes.

Improving powerline safety and targeted arson reduction programmes may reduce some wildfire ignitions but there is still potential for houses to be destroyed by wildfires, particularly during extreme weather conditions. Fuel management and suppression
resources may reduce fire spread but these are most effective under more benign weather conditions (Price and Bradstock 2012; Penman et al. 2013c). Containment success is more likely when suppression resources reach the fire when it is small in size (Arienti et al. 2006; Plucinski 2012, 2013). The early detection of ignitions and the placement of resources in strategic locations to minimise response time (Haight and Fried 2007) may improve suppression effectiveness. Other measures are centred around increasing the resilience of houses to wildfire impacts, e.g. reducing the exposure of houses to wildfire attack by development planning and building controls, and educating residents on preparing their property for wildfire. Land use and zoning measures can be used to prevent housing developments from occurring in wildfire-prone areas or require houses to comply with building construction standards and fire protection measures (Hughes and Mercer 2009; Moritz et al. 2014; Butsic et al. 2015). Designing or retrofitting houses to prevent ember penetration will improve the chance of a house’s survival in a wildfire as embers are the predominant mechanism of house ignitions from wildfires (Cohen 2000; Blanchi and Leonard 2008; Moritz et al. 2014). Reducing potential radiant heat and flame exposure can be achieved by siting the house relative to flammable vegetation and building construction standards (Cohen 2000; Blanchi and Leonard 2008; Moritz et al. 2014). House survival from a wildfire is more likely if the vegetation in a 40m zone surrounding a house is well maintained and there are no combustible objects within this zone (Cohen 2000; Blanchi and Leonard 2008; Gibbons et al. 2012). Active defence of the house will also increase its chance of survival (Wilson and Ferguson 1986; Blanchi and Leonard 2008; Whittaker et al. 2013) although residents must be well prepared both physically and mentally if they are to undertake fire suppression activities (Penman et al. 2013d).

Our study has highlighted the major wildfire ignition causes that result in destroyed houses, however focussing on this area only, will not reap the greatest reduction in houses destroyed by wildfires. A combination of fire management, planning and resident actions is required to reduce the number of houses destroyed by wildfires.

3.6 Supporting Information

See Appendix B for supplementary information.
3.7 Acknowledgements

We thank the New South Wales Rural Fire Service and the Victorian Department of Environment, Land, Water and Planning for providing the wildfire ignition records used in this study. We also thank the two reviewers for their helpful and constructive suggestions.
Chapter 4

4 SUPPRESSION RESOURCE DECISIONS ARE THE DOMINANT INFLUENCE ON CONTAINMENT OF AUSTRALIAN FOREST AND GRASS FIRES

4.1 Abstract
Fire agencies aim to contain wildfires before they impact on life, property and infrastructure and to reduce the risk of damage to the environment. Despite the large cost of suppression, there are few data on the success of suppression efforts under varying weather, fuel and resource scenarios. We examined over 2200 forest and 4600 grass fires in New South Wales, Australia to determine the dominant influences on the containment of wildfires. A random forest modelling approach was used to analyse the effect of a range of human and environmental factors. The number of suppression resources per area of fire were the dominant influence on the containment of both forest and grass fires. As fire weather conditions worsened the probability of containment decreased across all fires and as fuel loads and slope increased the probability of containment decreased for forest fires. Environmental controls limit the effectiveness of wildfire management. However, results suggest investment in suppression resources and strategic fuel management will increase the probability of containment.

4.2 Introduction
Wildfires have caused significant loss of human lives and property and billions of dollars of economic losses across the globe (Gill et al. 2013). For example, destructive wildfires reported in the media in 2017 occurred in Spain, Portugal, South Africa, USA, Canada, Chile, New Zealand and Australia. The cost of impact can be reduced through fire management actions. Fire agencies deploy resources to suppress wildfires to protect life, property and infrastructure from impact by fire and reduce the risk of damage to the environment. Active suppression of fires can reduce the total area burnt (Cumming 2005; DeWilde and Chapin 2006) however, fires that escape initial attack can become large and costly to manage (Gebert and Black 2012; Calkin et al. 2013). Therefore, it is important to know what factors influence the probability of containment of fires.

Environmental factors can have a strong influence on the probability of containment. Fuel type (Hirsch et al. 2004; Arienti et al. 2006), fuel load (McCarthy et al. 2012; Plucinski
weather conditions (Arienti et al. 2006; Plucinski 2012, 2013) and slope (McCarthy et al. 2012) may influence the probability of containment. These factors are likely to be important because they all influence various aspects of fire behaviour - rate of spread, flame height, intensity and likelihood of spotting (Cruz et al. 2015). All these factors can influence fire containment difficulty. The faster a fire spreads, the larger its perimeter grows, requiring crews to establish a longer length of control line to contain the fire compared with a slower spreading fire (e.g. Parks 1964; Weber et al. 2009). The higher the fire’s intensity, the higher the flame height, the more likely spot fires will occur, and the less likely ground crews can extinguish the fire directly at the fire edge. The upper limit for direct attack of fires with hand tools is estimated to be 500 kW/m and for ground-based crews around 2000-4000 kW/m (Hirsch and Martell 1996). Fire intensity also influences the rate of control line construction. For example, Loane and Gould (1986) found a machine crew (D6 dozer with tankers and 9 fire fighters) constructed a control line at a maximum and constant rate up to 500 kW/m but this rate drops sharply to zero for intensities above 2000 kW/m. They found a similar pattern for hand crews with control line construction occurring at a constant rate until falling sharply to zero for intensities above 800 kW/m.

Decisions around suppression response are also known to influence the probability of containment. One of the key decisions is resource placement as resource response time (Arienti et al. 2006; Plucinski 2012) and fire area when crews arrive at the fire (Arienti et al. 2006; McCarthy et al. 2012; Plucinski 2012, 2013) can influence the probability of containment. A fast response time will lead to a smaller fire area when crews begin suppression operations which could be important when a fire is spreading rapidly. However, under conditions conducive to a low rate of spread, response time would be less influential as the fire size will change little over time. Another key decision is the number and type of resources to deploy to the fire as this relates to the rate of control line construction (Fried and Gilless 1989; McCarthy et al. 2003). More resources can create a control line faster and for successful containment to occur the rate of construction needs to exceed the rate of fire perimeter growth (Weber et al. 2009).

There are few studies globally that have quantified the influence of various environmental and human factors on the probability of suppression. In Australia, existing studies have used limited datasets. These studies have considered suppression success in either forest
(McCarthy et al. 2012; Plucinski 2012) or grass (Plucinski 2013) fires but have used a maximum of 334 fires. We aimed to conduct a comprehensive assessment of the factors affecting containment using a much larger data set (n=6837) and a broader range of factors than has previously been attempted. No comprehensive data that contains all relevant factors was available, so we used data that is consistently available from fire incident reports plus weather, fuel load and topographic data. Specifically, we asked what is the relative importance of environmental and human factors in containing grass and forest fires at various time periods from when the first ground crews arrived at the fire. From the findings of previous studies, we hypothesise that:

1. Factors which influence fire behaviour – fuel, weather and topography – will be important in determining the probability of containment.
2. The number of resources and the response time will be important in determining the probability of containment.

4.3 Materials and methods
The study area was the state of New South Wales in Australia. The population is largely city based with over 60% of the population residing in the greater Sydney area (http://www.censusdata.abs.gov.au, Accessed April 2017). Other high population centres are along the coastal fringe and nearby inland areas. Large areas of western New South Wales are sparsely populated (Collins et al. 2015). The natural vegetation of the study area (Fig. 4.1) is varied with Eucalyptus spp. dominant forests and woodlands in the coastal and mountainous hinterland areas (Keith 2004). The climate in these areas ranges from temperate to moist subtropical and these forests can burn at very high intensities (Murphy et al. 2013). The dominant species in the semiarid woodlands in central and western New South Wales are Eucalyptus, Casuarina, Acacia and Callitris spp. (Keith 2004). These woodlands burn infrequently at low to medium intensities (Murphy et al. 2013). Chenopod shrublands dominate the arid and semiarid regions of western New South Wales where rainfall or local soil moisture is too low to support tree-dominated vegetation (Keith 2004). Chenopods typically burn as low intensity fires although fires are rare events (Murphy et al. 2013). The grasslands are predominately perennial tussock grasses (Keith 2004) which burn as low intensity fires (Murphy et al. 2013). Agriculture areas cleared of natural vegetation are largely pasture and croplands which burn infrequently as low intensity grass fires (Murphy et al. 2013).
Fire and response data were taken from fire incident records held by the New South Wales Rural Fire Service who are responsible for the suppression of wildfires across approximately 95% of New South Wales, Australia. Only incident records contained in both the fire incident reporting system and incident management system were included in the study as both sets of data were used to confirm the reported information. Incidents where the time the first ground crews arrived at the fire was listed as 0 were removed as this is a default value for the incident reporting system i.e. the recorder may have failed to enter the actual value. Incidents where no tankers were tasked to the fire or where the fire incident report stated that ground crews delayed attacking the fire as the fire was either inaccessible or was not posing a threat to property were also removed. The study data included incident and response records from July 2005 to June 2013.

Figure 4.1 Location of study area and predominant natural vegetation in New South Wales (source: National Vegetation Information System ver. 4.1; Department of the Environment and Energy, http://www.environment.gov.au/land/native-vegetation/national-vegetation-information-system/data-products).
Predictor variables used in the study are defined in Table 4.1. The time the fire was contained was defined as the time when the fire is no longer spreading i.e. when the final fire area was reached. The response time refers only to when the first ground crews arrived at the fire. The peak number of firefighters and tankers at the incident was used as this is the only field available in the fire incident reporting system on the number of resources at the fire and the incident management system does not record the arrival and departure times of all resources over the duration of the fire. All firefighters and tankers tasked to the fire were assumed to be attempting to contain the fire as it was not possible to ascertain if some of these resources were used for other purposes such as property protection. Size/category of tankers, earth-moving machinery and aircraft despatched to the fire was not available. Earth-moving machinery only used to strengthen containment lines after the fire had been contained or to remove dangerous trees were not recorded as assisting in containing the fire. Aircraft only used to map the fire or to provide reconnaissance were not recorded as suppressing the fire. For analysis purposes, the peak number of tankers and firefighters were divided by the square root of the final fire area. This was done to enable comparison between fires and to scale the resources to the length of perimeter needing containment. The number of earth-moving machinery and aircraft used was converted to a binary factor as these resources were not used at every fire. Earth-moving machinery was used on 5% of grass fires and 24% of forest fires and aircraft used on 4% of grass fires and 27% of forest fires. Broad fuel type was either a grass or forest fire. Crop fires were included in grass fires and those classified as scrub or bush fires were included as forest fires.

The ignition cause was assigned to one of five cause types: deliberate, lightning, powerline, accidental and undetermined. Deliberate ignitions included arson and fires where it was suspected that they were intentionally lit. Powerline ignitions were due to fires starting because of powerlines clashing, arcing or vegetation or animals contacting the live parts of the network or breakage of wires, poles or other parts of the network. Accidental ignitions included all other human caused fires that were unintentionally started e.g. escapes from prescribed burns, camping or cooking fires, fires caused by equipment or machinery use or smoking. Undetermined cause fires included all fires where the fire cause was unknown or unreported.
### Table 4.1 Variables used in the study

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response time</td>
<td>Time between when the fire was reported and ground crews arriving at the fire (min)</td>
</tr>
<tr>
<td>Containment time</td>
<td>Time between ground crews arriving at the fire and the fire contained (min)</td>
</tr>
<tr>
<td>Tpa</td>
<td>The peak number of tankers at the fire divided by the square root of the final fire area in hectares</td>
</tr>
<tr>
<td>FFpa</td>
<td>The peak number of firefighters at the fire divided by the square root of the final fire area</td>
</tr>
<tr>
<td>EMM</td>
<td>Was earth moving machinery used to contain the fire? (yes or no)</td>
</tr>
<tr>
<td>Aircraft</td>
<td>Were aircraft used to contain the fire? (yes or no)</td>
</tr>
<tr>
<td>Fuel load</td>
<td>The estimated forest fuel load (t/ha) at the point of ignition. Estimated from time since fire data and fuel accumulation curves.</td>
</tr>
<tr>
<td>Ignition cause</td>
<td>Deliberate, lightning, powerline, accidental or undetermined</td>
</tr>
<tr>
<td>Fire load</td>
<td>The number of uncontained fires in the management district when the fire started (see Fig. 4.2 for district boundaries)</td>
</tr>
<tr>
<td>Slope</td>
<td>The estimated slope at the point of ignition (°) Estimated from a 30-m digital elevation model obtained from Geoscience Australia</td>
</tr>
<tr>
<td>Temperature</td>
<td>Air temperature recorded at 1500h on day of ignition (°) from the nearest available Bureau of Meteorology station</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>Relative humidity recorded at 1500h on day of ignition (%) from the nearest available Bureau of Meteorology station</td>
</tr>
<tr>
<td>Wind speed</td>
<td>Wind speed recorded at 1500h on day of ignition (km/h) from the nearest available Bureau of Meteorology station</td>
</tr>
<tr>
<td>GFDI</td>
<td>Grassland Fire Danger Index at 1500h on day of ignition. Calculated from equation in Noble et al. 1980.</td>
</tr>
<tr>
<td>FFDI</td>
<td>Forest Fire Danger Index at 1500h on day of ignition. Calculated from equation in Noble et al. 1980.</td>
</tr>
</tbody>
</table>

The fuel load at the ignition point was estimated for forest fires using fire history databases (NSW Government unpublished data) to delineate the time since fire, the vegetation class based on Keith (2004) using vegetation data (Vegetation Classes of NSW ver. 3.03, http://data.environment.nsw.gov.au/dataset/vegetation-classes-of-nsw-version-3-03-200m-raster-david-a-keith-and-christopher-c-simpc0917) and fuel accumulation relationships (Watson et al. 2012; Gordon and Price 2015). The grassland and forest fire danger indices combine ambient weather variables (temperature, relative humidity and wind speed) and fuel moisture (% curing for grass and drought factor for forest) to derive an index of the forward rate of spread and suppression difficulty of fires (Noble et al. 1980). For grass fires, the grassland fire danger index was calculated using 100% grass curing as there were no grass curing data available for the study.
Random forests were used to analyse the factors which influence the containment of fires (Breiman 2001). Random forests are an ensemble learning technique, a random subset of the predictor variables are used to develop individual classification trees that are assigned a class vote, and then the predictions from all trees are combined using majority vote (Breiman 2001). The model error is calculated by comparing the prediction of each tree with data held back during its development (out of bag samples) and then averaged over all observations (Cutler et al. 2007). Variable importance for a given variable is estimated by comparing increases in out of bag error when that variable is randomly permuted while all others remain unchanged (Cutler et al. 2007). Partial dependence plots provide a graphical representation of the marginal effect of a variable on the response and are developed for an individual predictor variable by fixing the values of this predictor and averaging the prediction function over all the combinations of observed values of the other variables in the model (Cutler et al. 2007).

Grass and forest fires were analysed separately, and a hierarchical order of models were developed to test the time to containment. The first model used all data (e.g. for forests) and tested whether containment was achieved within 2 hours of ground crews arriving at the fire (binary 0 or 1). Then those fires that were not contained within 2 hours were used as input to a model of containment between 2 and 4 hours. This same process of using the fires not contained in the previous time period as the input was repeated for containment between 4 and 12 hours and 12 to 24 hours. The time periods beyond 2 to 4 hours were not used for grass fires as there were too few records within these time periods to conduct an analysis. For each analysis, the data was randomly split into training (70%) and test (30%). The number of trees to grow and the number of variables randomly sampled at each split are random forest tuning parameters (Hastie et al. 2009). Therefore, ten-fold cross-validation was used on the training data for each time period to select the optimal settings for these parameters. The variable importance value (mean decrease in accuracy) was used to determine whether the variable should be included in the final model. Variable importance values close to zero indicate these variables contribute very little to the predictive accuracy of the forest and a negative variable importance value indicates that when this variable is randomly exchanged the predictive accuracy in the forest increases. Therefore, the variable with the lowest importance value was iteratively removed from the random forest model until all variables had an importance values > 2.
as measured by the mean decrease in accuracy (mda). The random forest model was developed using the training data and the accuracy of the resultant model was assessed using the test data.

All analyses were conducted using the R statistical package version 3.3.1 (R Core Team 2016). The R package caret (Kuhn et al. 2017) was used for the cross-validation to determine the random forest settings. The random forest models were generated using the R package randomForest (Liaw and Wiener 2002). The partial dependence plots were developed using the R package pdp (Greenwell 2017). The model fit was measured by calculating the area under the curve (AUC) of the Receiver Operating Characteristic plot (Hanley and McNeil 1982) using the R package pROC (Robin et al. 2011). AUC values range from 0 to 1 where 0.5 represents a completely random prediction, 0.5-0.6 = fail, 0.6-0.7 = poor, 0.7-0.8 = fair, 0.8-0.9 = good and 0.9-1 = excellent (Thuiller et al. 2003).

4.4 Results
A total of 2219 forest fires and 4618 grass fires (Fig. 4.2, Table 4.2) were available for the study. Most grass fires were contained within 2 hours of ground crews arriving at the fire (95%) and only 1% of grass fires were not contained within 4 hours. In contrast, 50% of forest fires were contained within 2 hours and 13% were still uncontained after 24 hours. The summary statistics of variables used in the modelling are included in Appendix C Table C1.

<table>
<thead>
<tr>
<th>Containment Time</th>
<th>Fuel type</th>
<th>No. of fires</th>
<th>No. of fires contained</th>
<th>% Contained</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;= 2 hours</td>
<td>Forest</td>
<td>2219</td>
<td>1100</td>
<td>49.6</td>
</tr>
<tr>
<td>&gt;2 &amp; &lt;= 4 hours</td>
<td>Forest</td>
<td>1119</td>
<td>370</td>
<td>33.1</td>
</tr>
<tr>
<td>&gt;4 &amp; &lt;= 12 hours</td>
<td>Forest</td>
<td>749</td>
<td>291</td>
<td>38.7</td>
</tr>
<tr>
<td>&gt;12 &amp; &lt;= 24 hours</td>
<td>Forest</td>
<td>459</td>
<td>171</td>
<td>37.3</td>
</tr>
<tr>
<td>&lt;= 2 hours</td>
<td>Grass</td>
<td>4618</td>
<td>4397</td>
<td>95.2</td>
</tr>
<tr>
<td>&gt;2 &amp; &lt;= 4 hours</td>
<td>Grass</td>
<td>221</td>
<td>172</td>
<td>77.8</td>
</tr>
</tbody>
</table>
Ground crews on average took longer to arrive at the fire for forest fires compared to grass fires (35 min for forest, 23 min for grass), they took longer to contain the fire (762 min for forest, 52 min for grass) and the mean fire area was larger (183 ha for forest, 20 ha for grass). For both forest and grass fires the average response time (50 min for forest, 30 min for grass) and containment time (1078 min for forest, 73 min for grass) was highest for lightning caused fires (Appendix C Table C2). The fire load was zero (i.e. no other fires were uncontained in the district when the fire started) for 74% of forest fires and 83% of grass fires.

4.4.1 Determinants of forest fires contained within 2 hours

The most important variables for the random forest model for forest fires contained within 2 hours of ground crews arriving at the fire were earth-moving machinery, aircraft and the number of tankers and firefighters per ha of fire (Fig 4.3). Fuel load and slope were the next most important variables, followed by fire weather variables and response time.
Ignition cause had the lowest variable importance value (mda 3.5). Fire load was excluded from the final random forest model because it had a very low importance value (mda 1.8). For both earth-moving machinery and aircraft, a fire was less likely to be contained if these resources were working on the fire (Fig 4.4). When these resources were used for forest fires, 20% of fires that used aircraft and 13% of fires that used earth-moving machinery were contained within 2 hours whereas 60% of fires were contained within 2 hours without using aircraft and 61% were contained without using earth-moving machinery. The probability of containment of a forest fire increased as the number of tankers per ha of fire increase (Fig. 4.4) although the relationship flattens when > 4 tankers per ha of fire are present (Probability of containment (P) = 0.58). Similarly, for the number of firefighters per ha of fire, the probability of containment increased as the number of firefighters increased but the relationship flattens when the number of firefighters per ha of fire is > 5 (P = 0.53). A forest fire had a higher probability of containment within 2 hours if the fuel load < 10 t/ha (P = 0.57) and slope < 8° (P = 0.50) compared to when the fuel load > 20 t/ha (P = 0.42) and slope > 15° (P = 0.42, Fig 4.4).

The partial response for forest fire danger index indicates the probability of containment increases when the index < 10 (Pmax = 0.53) and then flattens when the index >10 (P = 0.48). Response time increases when response time <25 min (Pmax = 0.52) and then flattens when the response time > 25 min (P = 0.47). There was only a 2% difference between the probability of containment for ignition causes (lightning P = 0.48, powerlines P = 0.50, Fig. 4.4).

The training error for the random forest model for forest fires contained within 2 hours was 21.6% and the model had a good fit with an AUC of 0.87 (Table 4.3). The test set error rate was 22.1% and the model had a good fit for the test data with an AUC of 0.85 (Table 4.3).
Figure 4.3 Variable importance as measured by the mean decrease in accuracy in predictions of random forest models for containment time of forest and grass fires. RH = relative humidity, FFDI = forest fire danger index, GFDI = grassland fire danger index, EMM = earth-moving machinery, FFpa = number of firefighters per square root of the final fire area, Tpa = number of tankers per square root of final fire area.
Figure 4.4  Partial dependence plot for variables in the random forest model for containing forest fires within 2 hours of ground crews arriving at the fire. Variables are ranked in order of importance. EMM = earth-moving machinery, Tpa = number of tankers per square root of final fire area, FFpa = the number of firefighters per square root of final fire area, FFDI = forest fire danger index, RH = relative humidity. Acc = accidental, Del = deliberate, Lgt = lightning, Pow = powerline, Und = undetermined.
Table 4.3  Random forest model number of variables used at each split, number of trees grown, training and test error rate and AUC for containment of forest and grass fires.

<table>
<thead>
<tr>
<th>Containment Time</th>
<th>Fuel type</th>
<th>No. of variables</th>
<th>No. of trees</th>
<th>Training Error</th>
<th>Training AUC</th>
<th>Test error</th>
<th>Test AUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;= 2 hours</td>
<td>Forest</td>
<td>4</td>
<td>1000</td>
<td>21.6</td>
<td>0.87</td>
<td>22.1</td>
<td>0.85</td>
</tr>
<tr>
<td>&gt;2 &amp; &lt;= 4 hours</td>
<td>Forest</td>
<td>2</td>
<td>2000</td>
<td>25.0</td>
<td>0.82</td>
<td>25.3</td>
<td>0.81</td>
</tr>
<tr>
<td>&gt;4 &amp; &lt;= 12 hours</td>
<td>Forest</td>
<td>2</td>
<td>500</td>
<td>28.6</td>
<td>0.78</td>
<td>22.7</td>
<td>0.81</td>
</tr>
<tr>
<td>&gt;12 &amp; &lt;= 24 hours</td>
<td>Forest</td>
<td>2</td>
<td>2000</td>
<td>31.2</td>
<td>0.74</td>
<td>35.5</td>
<td>0.67</td>
</tr>
<tr>
<td>&lt;= 2 hours</td>
<td>Grass</td>
<td>3</td>
<td>1000</td>
<td>4.76</td>
<td>0.86</td>
<td>4.91</td>
<td>0.87</td>
</tr>
<tr>
<td>&gt;2 &amp; &lt;= 4 hours</td>
<td>Grass</td>
<td>2</td>
<td>1500</td>
<td>24.0</td>
<td>0.62</td>
<td>23.9</td>
<td>0.73</td>
</tr>
</tbody>
</table>

4.4.2  Determinants of forest fires contained within 2 to 4 hours

The most important variables for the random forest model for forest fires contained within 2 to 4 hours of ground crews arriving at the fire were the number of tankers and firefighters per ha of fire and earth-moving machinery (Fig 4.3). Fuel load and slope were the next most important variables (Fig 4.3). Fire load and wind speed were excluded from the final random forest model because of negative variable importance values. The partial responses for the probability of containment within 2 to 4 hours of ground crews arriving at the fire for each variable (Appendix C Fig. C1) show similar relationships to the plots for probability of containment within 2 hours (Fig 4.4), but the probability of containment within 2 to 4 hours was lower for each variable. For example, the maximum probability of containment for the 2 to 4 hour time period for the number of tankers and firefighters per ha of fire was 0.49 and 0.44 compared with 0.59 and 0.54 for the within 2 hour time period. The training error for the random forest model for forest fires contained within 2 to 4 hours was 25.0% and the model had a good fit with an AUC of 0.82 (Table 4.3). The test error rate was 25.3% and the model had a good fit for the test data with an AUC of 0.81 (Table 4.3).

4.4.3  Determinants of forest fires contained within 4 to 12 hours

The most important variables for the random forest model for forest fires contained within 4 to 12 hours of ground crews arriving at the fire were the number of tankers and firefighters per ha of fire (Fig 4.3). Wind speed, fire load and ignition cause were excluded from the final random forest model because of low variable importance values (mda 1.3, 1.4 and 1.6 respectively). The main difference in variable importance rankings for this containment time period compared to the previous time periods was that slope had a
higher importance ranking (third most important for 4 to 12 hours, sixth for within 2 hours and fifth for 2 to 4 hours) and fuel load a lower importance ranking (eighth most important for 4 to 12 hours, fifth for within 2 hours and fourth for 2 to 4 hours). The partial responses for the probability of containment within 4 to 12 hours of ground crews arriving at the fire for each variable (Appendix C Fig. C2) show similar relationships to the plots for probability of containment within 2 hours (Fig 4.4) but the probability of containment within 4 to 12 hours was slightly lower for each variable. For example, the maximum probability of containment for the number of tankers and firefighters per ha of fire was 0.54 and 0.52 for the 4 to 12 hour time period compared with 0.59 and 0.54 for the within 2 hour time period. The training error for the random forest model for forest fires contained within 4 to 12 hours was 28.6% and the model had a fair fit with an AUC of 0.78 (Table 4.3). The test set error rate was 22.7% and the model had a good fit for the test data with an AUC of 0.81 (Table 4.3).

4.4.4 Determinants of forest fires contained within 12 to 24 hours

The most important variables for the random forest model for forest fires contained within 12 to 24 hours of ground crews arriving at the fire were the number of firefighters and tankers per ha of fire (Fig 4.3). In contrast to the previous time periods, fire load was included in the final random forest model and was the fourth most important variable in the model (Fig 4.3). The partial response for the probability of containment within 12 to 24 hours of ground crews arriving at the fire for fire load (Appendix C Fig. C3) show a fire is less likely to be contained when 2 or more fires are uncontained in the district (P ≤ 0.31) compared to when 1 (P = 0.38) or 0 (P= 0.37) other fires are uncontained in the district. Wind speed and response time were excluded from the final random forest model because of negative variable importance values. However, the results of this random forest model should not be relied upon as the training error for the model was 31.2% and the model had a fair fit with an AUC of 0.74 (Table 4.3). The test set error rate was 35.5% and the model had a poor fit for the test data with an AUC of 0.67 (Table 4.3).

4.4.5 Determinants of grass fires contained within 2 hours

The most important variable for the random forest model for grass fires contained within 2 hours of ground crews arriving at the fire were the number of tankers per ha of fire (Fig. 4.3). Weather variables, the number of fire fighters per ha of fire and aircraft were the
The most important variables for the random forest model for grass fires contained within 2 to 4 hours of ground crews arriving at the fire were earth-moving machinery and aircraft (Fig. 4.3). Fire load, ignition cause, wind speed, and the number of firefighters per ha of fire were excluded from the final random forest model because of negative variable importance values. The partial responses for the probability of containment within 2 to 4 hours of ground crews arriving at the fire for each variable (Appendix C Fig. C4) show similar relationships to the plots for probability of containment within 2 hours (Fig 4.5) but the probability of containment within 2 to 4 hours was lower for each variable. For example, the maximum probability of containment for the 2 to 4 hour time period for the number of tankers per ha of fire was 0.83 compared with 0.97 for the within 2 hour time period. The results of this random forest model should not be relied upon as the training model AUC was poor (0.62) and the model had a good fit for the test data with an AUC of 0.73 (Table 4.3).
Figure 4.5 Partial dependence plot for variables in the random forest model for containing grass fires within 2 hours of ground crews arriving at the fire. Variables are ranked in order of importance. Tpa = number of tankers per square root of final fire area, RH = relative humidity, FFpa = the number of firefighters per square root of final fire area, GFDI = grassland fire danger index, EMM = earth-moving machinery, Acc = accidental, Del = deliberate, Lgt = lightning, Pow = powerline, Und = undetermined.

4.5 Discussion

Human factors i.e. the number of resources per ha of fire, were the dominant influence on the containment of both forest and grass fires. Environment factors i.e. fuel load and slope had a strong influence on the probability of containment of forest fires and weather conditions were also influential in containing both forest and grass fires. These results are similar to previous studies that found increasing crew size increased the probability of containment (Hirsch et al. 2004; McCarthy et al. 2012) and reduced average fire area (Podur and Martell 2007; Penman et al. 2013c). The probability of containment of forest fires decreases as fuel load (McCarthy et al. 2012; Plucinski 2012), slope (McCarthy et
(Arienti et al. 2006; Plucinski 2012; Penman et al. 2013c). Slope and response have only a minor influence on the probability of containment of grass fires (Plucinski 2013).

Unsurprisingly, the more resources available to control the fire, the more likely the fire will be contained. Grass fires are generally easily accessible to tankers and containment is achieved by directly applying water to the fire edge. If the fire spread is too fast or the flame height too high, then direct attack is made on the flanks of the fire, working from the rear to the head (Luke and McArthur 1978; Cheney and Sullivan 2008). The more resources available, the faster the fire will be contained. Forest fires may be directly attacked at the fire edge if it is safe and accessible to firefighters or contained by indirect attack which involves burning back from control lines to provide an effective barrier against the main fire (Luke and McArthur 1978; Fried and Fried 1996). Indirect attack cannot be achieved unless a suitable control line is established, hence the more crews available to prepare the control line and ensure the back burn is contained within the control line, the faster the fire will be contained.

Fires are successfully contained when the fire spread has been stopped, therefore factors which influence fire spread, fuel load, weather conditions and topography (Cruz et al. 2015) are also important factors influencing fire containment. Our results align with Tolhurst and McCarthy (2016) who characterised fires burning when the fire danger index <50 as mostly fuel- and topography-dominated fires and fires burning when the fire danger index > 50 as mostly weather-dominated fires. In our study, fuel and topography were the dominant environmental variables in forest models with weather less important. However in our study, most (97%) forest fires occurred when the fire danger index < 50. In New South Wales, a fire danger index > 50 occurs on average only 1.9% days each year (calculated using 3pm weather data from the Bureau of Meteorology weather stations in NSW over a 30 year period from 1982-2013). Studies that focus on fires above FDI 50 find weather conditions are the strongest predictor of fire spread (e.g. Moritz et al. 2010; Jin et al. 2014; Price et al. 2015a) and therefore we may expect suppression effectiveness to be more strongly linked to fire weather in these conditions.

Probability of containment was reduced for fires that used earth-moving machinery and aircraft however this seems counterintuitive as these resources are commonly used for
rapid establishment of containment lines. However, the associated costs with these resources means that aircraft and earth-moving machinery are typically only used when firefighting conditions are difficult for ground crews to contain the fire due to the fast spread of the fire or difficulty in accessing the fire, or to protect people and property from the impact of fire (Plucinski et al. 2012). Therefore, these resources are usually only tasked to fires which are predetermined by fire managers as potentially being difficult to control or are at risk of impacting on houses. It is possible that for some of the fires in the study that used these resources, the time to containment would have been much greater if these resources were not available (Plucinski et al. 2012).

Response time had a limited influence on the probability of containment in contrast to previous studies (Arienti et al. 2006; Plucinski 2012). Our study only included fires where ground crews were deployed immediately on notification of the fire whereas the other studies included all fires regardless of whether there was a delay in sending crews to the fire. The median and maximum response times in our study were 27 and 241 minutes for forest fires (Appendix C Table C1), whereas the values were 29 and 89530 minutes in Arienti et al. (2006) and 40 and 690 minutes for ground crews and 60 and 1320 minutes for aircraft in Plucinski (2012). Plucinski (2012) only included fires where aircraft were used in the initial attack phase, so his data may be skewed to the more difficult fires to contain. The importance of response time is also dependent on the fire behaviour. A long response time on days when the fire weather conditions are benign is irrelevant as the fire would be spreading slowly with a low intensity and relatively small perimeter to contain when crews arrived. Likewise, a short response time when the fire weather conditions are extreme may also be irrelevant as the fire may have rapidly spread and be too intense for crews to contain at initial attack.

Containment of fires could be improved by modifying the number of resources available, the response time of these resources and/or the fuel load. Fire managers determine the number and type of resources deployed to a fire based on location of the fire, the values at risk, the likely fire behaviour and the total number of resources available. One way of increasing resources without large increase in costs is to shift resources around when there is a high likelihood of ignitions. The number of ignitions increase as the fire weather severity increases (Penman et al. 2013b; Plucinski 2014) so it may be beneficial to move resources from areas where the fire danger index is low to areas where the fire danger
index is higher, particularly on weekends and public holidays as these are the days when
the highest number of human-caused ignitions occur (Albertson et al. 2009; Prestemon et

Resource response time can be improved by the early detection of fires and the strategic
location of resources. The earlier a fire is reported and the more information that is known
about the fire, including its precise location, accessibility to ground crews, size and fire
behaviour, the more likely a fire will be contained at a small size (Martell 2001).

Investment in fire detection and monitoring systems e.g. fire towers, patrol aircraft, and
ground-based, manned airborne-based, satellite-based and unmanned aerial vehicles
remotely sensed systems (Yuan et al. 2015; Hua and Shao 2017; Yuan et al. 2017) can
improve response times. Encouraging the public to report fires can also improve resource
response time.

Fire managers can reduce the fuel load by clearing, grazing, slashing of grassy vegetation,
mechanical treatments of forests and prescribed burning and reduce the probability of
containment. Reducing the fuel load can facilitate fire suppression efforts by decreasing
the rate of spread, flame height and intensity (Fernandes and Botelho 2003). Although,
this effect diminishes as the time since treatment and fire weather severity increases (e.g.
Price and Bradstock 2010, 2012; Penman et al. 2013c; Tolhurst and McCarthy 2016) and
simulation studies have shown that fuel management is less effective at reducing the area
of moderate to high intensity unplanned fire and total area burned than efforts to prevent
or quickly extinguish wildfire ignitions and year to year weather variability (Cary et al.
2009; Cary et al. 2017). To be effective, a fire must encounter a treated patch while in a
fuel reduced state and under weather conditions that will allow suppression resources to
contain the fire. In the Sydney basin, Price and Bradstock (2010) found that 22% of
treated patches encountered a fire within 5 years of treatment and there was a 10% chance
that the fire would stop in the treated patch. Therefore, like the strategic placement of
resources, fuel reduction treatments should be targeted to areas where fire ignitions are
predicted to occur. Human-caused ignitions are most likely to occur close to population
centres and roads (e.g. Syphard et al. 2008; Narayananaraj and Wimberly 2012; Penman et
al. 2013b; Collins et al. 2015) which suggests that fuel treatments should be placed close
to the urban interface (Gibbons et al. 2012; Penman et al. 2014a). Lightning-caused
ignitions are more likely to occur at high elevation sites away from population centres
Targeting fuel treatments in these areas may be effective in improving the probability of fire containment provided that it is not across a broad area of the landscape given the relatively low fire encounter rates.

The resolution of the available data imposed some constraints on the study. Only the response time for the first crews that arrived at the fire was available, so it was not possible to adjust the number of resources undertaking fire suppression based on when they arrived at the fire. It was also assumed all firefighters and tankers were actively engaged in fire suppression. For small fires, these limitations are likely to have had minimal impact on the results, however this may not be the case for large fires where additional resources may have taken some considerable time to arrive at the fire or crews are diverted to property protection. We tried to control for the variable number of resources available over time by dividing the resources by the square of fire area, but this does not completely solve the problem. These limitations could be overcome if resources were tracked using global positioning systems (GPS). If GPS tracking was available, then resource arrival and departure times and the type/category of resource is known but additional information on the tasks undertaken at the fire would still be needed. GPS tracking of aircraft has become increasingly available in recent years, but these are not generally tagged with what tasks the aircraft did at the fire e.g. water-bombing, reconnaissance, transporting firefighters and equipment, and when they were undertaking each task. Similarly, for tankers GPS tracking would need to identify when the crew were undertaking containment operations and when they were undertaking other tasks e.g. property protection, reconnaissance, mop up and patrol.

4.6 Conclusion

Our study demonstrated that resources per ha of fire and weather conditions were the most important factors influencing the probability of containment of grass fires and forest fires, these factors plus fuel load and slope for forest fires were the most important factors. Of these, only the number of resources available and fuel load can be modified by fire managers and the effectiveness of these management actions may be diminished by the encounter rate of fires and weather conditions. Targeting fuel treatments and locating resources to areas where fire ignitions are predicted to occur may be effective in improving the probability of fire containment. There are costs and benefits associated
with increasing prevention and suppression resources that require further study. Improvements in response data collection, particularly the timing of resource arrival, the type/category of the resource and activities undertaken by the resource, is required to further assist managers in determining the appropriate level of response to despatch to fires and support cost effective use of resources.

4.7 Acknowledgements

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Chapter 5

5 EXAMINING THE RELATIVE EFFECTS OF MITIGATION AND RESPONSE STRATEGIES TO REDUCE THE LIKELIHOOD OF HOUSE LOSSES FROM WILDFIRES.

5.1 Abstract
Increasingly people are living in areas that place them at risk from the devastating impact of wildfires. Fire management agencies use a range of strategies to reduce wildfire risk. However, there has been little quantification of the relative risk reduction provided by combinations of treatments. A Bayesian Network model was developed to quantify the relative influence of mitigation and response strategies on the likelihood of house loss from forest and grass fires in New South Wales bioregions. Existing datasets and empirical models were used to determine the likelihood of ignition, containment and impact on houses. We investigated the relative reduction in risk from investment in arson and powerline ignition prevention strategies, prescribed burning, suppression resources and suppression response time. Within bioregions, the annual risk of house losses was 3 or 4 times higher for forest fires than grass fires. Increasing the number of suppression resources was more effective at reducing house loss risk than both ignition management and fuel management. When the forest fire danger index >50, the risk of house losses increased for both forest and grass fires but the effectiveness of mitigation and suppression treatments only decreased for forest fires. Agencies have limited budgets to implement fire mitigation and suppression programmes. Results of this study should be combined with a cost benefit analysis of treatment options to inform investment decisions.

5.2 Introduction
Many countries have experienced the devastating effects of wildfires in the last decade. Examples include the 2009 Black Saturday fires in Australia (Teague et al. 2010), the 2016 Fort McMurray fire in Canada (Landis et al. 2018), the 2017 fires in USA (Nauslar et al. 2018), Chile and Portugal (Gomez-Gonzalez et al. 2018). These fires caused multiple fatalities, the loss of 1000s of homes and commercial structures, the evacuation of 1000s people during the event and had major social and economic impacts. Communities and individuals can take many years to recover from the impacts of wildfires, rebuilding houses is often a slow process (Ireton et al. 2014; Alexandre et al.
2015; Mockrin et al. 2015) and many residents, including children and firefighters suffer post-traumatic stress disorder after wildfires (McDermott et al. 2005; Marshall et al. 2007; Lewis et al. 2015; Psarros et al. 2017; Psarros et al. 2018). Wildfire impacts are likely to increase due to population growth, more houses being built in the wildland-urban interface (Moritz et al. 2014; Radeloff et al. 2018) and more frequent occurrences of conditions favourable to wildfires as a result of climate change (Flannigan et al. 2009; Clarke et al. 2011; Bryant and Westerling 2014).

Fire management agencies use a range of strategies to reduce the likelihood of wildfires occurring and reduce the impact of wildfires on humans and the environment. These strategies involve three broad activities: prevention/mitigation, preparedness and response (McLoughlin 1985; Emergency Management Australia 2004). Prevention/mitigation activities focus on strategies that either reduce the likelihood and spread of fires (e.g. ignition and fuel management) or reduce the vulnerability of assets that may be exposed to fire (e.g. land use planning and building design) (Kanowski et al. 2005). Ignition management includes restricting the use of fire e.g. declaring a total fire ban (usually for a 24 h period) and requiring permits to light a fire in the open during the fire danger period (typically declared for several months at the onset of warmer weather), restricting activities that could start fires e.g. machinery and equipment use (Luke and McArthur 1978; Plucinski 2014), restricting access to wildfire-prone areas, encouraging the public to report suspicious behaviour in these areas and arson prevention programmes (Muller 2009). Fuel management includes prescribed burning, mechanical treatments of forests, slashing of grassy vegetation, clearing and grazing (e.g. Luke and McArthur 1978; Fernandes and Botelho 2003; Reinhardt et al. 2008). Land use planning and building design to mitigate wildfire risk are incorporated into policies and planning instruments (March and Rijal 2015; Galiana-Martin 2017; Kocher and Butsic 2017) and in some jurisdictions some development applications are legislatively required to be referred to the local fire authority for analysis and direction (e.g. New South Wales Rural Fires Act 1997). Preparedness activities ensure that firefighting agencies and communities are ready to respond to wildfires e.g. resource allocation, training programmes, test exercises, fire detection systems, pre-incident plans and community engagement programmes (e.g. Emergency Management Australia 2004; Eriksen and Prior 2011; Penman et al. 2013a; McCaffrey 2015). Response activities activate the
preparedness arrangements and plans to deal with wildfires e.g. firefighting activities, community warnings and emergency alerts (e.g. Emergency Management Australia 2004; Plucinski 2012; McLennan et al. 2015; McCaffrey et al. 2018).

The extent of mitigation activities undertaken by fire management agencies to protect life, property and the environment from wildfires is limited by budgets and other constraints. It is not possible to control access to all wildfire-prone areas or prevent all ignitions. Fuel management activities are constrained by legislative, social, economic and logistical factors (Penman et al. 2011a; Ryan et al. 2013). Environmental legislation to protect endangered and threatened flora and fauna, soil and water, and air pollution restricts where, when and how fuel management activities can be undertaken (Stephens and Ruth 2005; Penman et al. 2011a; Ryan et al. 2013). Fuel reduction activities are generally well accepted by the public (McCaffrey et al. 2013; Gill et al. 2015) although acceptability varies between different interest groups, the treatment technique and location of treatment (McCaffrey et al. 2008). Prescribed burning in the urban interface zone are more expensive per hectare than landscape prescribed burns (Berry et al. 2006; Penman et al. 2014a) as these are typically smaller in size and require more resources per hectare to manage and contain the fire. Prescribed burning operations are conducted when the fuel moisture and weather conditions are favourable to minimise the chance of a fire escaping control lines. However, these conditions are infrequent throughout the year, and even when conditions are suitable, it may not be possible to conduct burns due to personnel unavailability or potential smoke impacts (Stephens and Ruth 2005; Penman et al. 2011a; Ryan et al. 2013). Land use planning and building design regulations are typically not retrospective and only apply to new developments. Most houses in wildfire-prone land in Australia pre-date these regulations, so unless the property owner voluntarily decides to retrofit their house, most houses do not comply with wildfire construction standards. However, most property owners are not willing to pay the full costs required to retrofit their houses (Penman et al. 2017).

Understanding how to reduce risk to life, property and the environment is important. The social and economic impacts of wildfires (Stephenson et al. 2013), increasing cost of fire suppression activities (Gebert and Black 2012), agency budgetary pressures (Stephens and Ruth 2005), increasing public scrutiny both through the media and via judicial inquiries (Teague et al. 2010; Eburn and Dovers 2015) and increasing levels of litigation
(Eburn and Cary 2017) have driven wildfire management planning to be undertaken within a risk based framework. It is therefore important to quantify the effectiveness of mitigation and suppression activities and what are the optimum mixes of mitigation and suppression strategies so that fire managers can make informed decisions about whether to accept or treat the risk (Purdy 2010).

Bayesian Network models are increasingly being used to assess risk, evaluate management alternatives and investigate the ecological impacts of wildfires and prescribed burning. For example, they have been used to assess the factors influencing wildfire occurrence (Dlamini 2010; Bashari et al. 2016; Papakosta and Straub 2016), likelihood of house losses from wildfires (Papakosta et al. 2017), relative influences of management strategies on large fires (Penman et al. 2011b), factors influencing wildfires at the wildland-urban interface (Penman et al. 2014b), optimal location of prescribed burning treatments to reduce wildfire risk to houses (Penman et al. 2014a), strategies at the wildland-urban interface to reduce wildfire risk to houses (Penman et al. 2015) and the ecological consequences of wildfires (Howes et al. 2010; Ayre and Landis 2012; Hradsky et al. 2017). Bayesian Network models are ideally suited to evaluating risk reduction from management strategies as the expected outcome of each treatment decision can be quantitatively determined (Marcot et al. 2001).

In this study, we develop a Bayesian Network model to quantify the relative influence of mitigation and response strategies on the likelihood of house loss from wildfires. We investigate the effectiveness of ignition management (arson and powerline), fuel management (prescribed burning) and suppression management (number of resources and response time) on reducing the likelihood of house loss from forest and grass fires within New South Wales (NSW) bioregions. NSW has a history of wildfires resulting in house losses, with 767 houses destroyed in 84 wildfires since 2001 (Collins et al. 2016 and NSW Rural Fire Service data for recent fires). We determine which combination of treatments provide the greatest reduction in risk of house loss from wildfires. We examine how effective these treatments are under severe weather conditions (forest fire danger index >50) where over 90% of house losses in Australia have historically occurred (Blanchi et al. 2010).
5.3 Methods
The study covered all bioregions in the state of NSW, Australia (Fig. 5.1). The coastal and hinterland vegetation is eucalypt dominated temperate forest and woodlands that typically burn at intensities up to 5000 kW/m but can burn under extreme conditions at very high intensities around 50000 kW/m (Murphy et al. 2013). The central cleared areas are pastures and croplands and the western vegetation is semiarid woodlands, chenopod shrublands and grasslands. These areas all typically burn infrequently at low intensities (Murphy et al. 2013). The NSW population is highly urbanised with over 60% of the population residing in the Sydney Basin bioregion. Other relatively high population centres occur in cities along the coast and nearby hinterland areas. The population density generally decreases from east to west, with the central bioregions moderately populated and the western bioregions sparsely populated (Fig. 5.2).

5.3.1 Bayesian Networks
Bayesian Networks are graphical models of variables and their interactions for an outcome of interest such as the likelihood of house loss. The variables are represented as nodes in the diagram and can be assigned one or more values (or states). Directed arcs (or links) are drawn to show the interactions between nodes. The terminology parent or child is used to describe the position of a node in the structure, a node is a parent of a child if there is an arc from the former to the latter (Korb and Nicholson 2004). There are two main types of nodes, chance nodes and decision nodes. Chance nodes have an associated conditional probability table which represent the probability or frequency with which a node takes on a discrete state, given the states of any parent nodes that interact with it (Marcot et al. 2001). For a parentless node (also known as a root node), the conditional probability table has a single probability distribution that represents prior knowledge on the likelihood of each state i.e. its prior probability (Korb and Nicholson 2004; Marcot et al. 2006). Decision nodes do not have conditional probability tables but instead have two or more discrete choices that influence the values of other variables (Marcot et al. 2001; Nyberg et al. 2006). Bayesian Networks predict outcomes expressed as likelihoods that can be used as the basis for risk management decisions (Marcot et al. 2001).
5.3.2 Conceptual model

A conceptual model (Fig. 5.3) for the Bayesian Network was constructed based on a fire process model developed by Penman et al. (2011b). This model shows the progression of a wildfire from ignition to causing a house loss. The output of the model is the likelihood of a house loss occurring. The conceptual model has three sub-models: an ignition likelihood model, a containment likelihood model and a house loss likelihood model. Ignitions can be derived from arson, powerlines, other accidental human causes and lightning. Once an ignition occurs, the fire may spread either as a forest fire or a grass fire and may be contained by suppression resources. If the fire is not contained it may result in a house loss. For modelling purposes, a grass fire could potentially spread to houses if it was not contained within 2 hours of fire crews arriving at the fire. For forest
fires, a 4 hour time period was used for containment as forest fires spread much slower than grass fires. Fire weather affected processes throughout the model, while fuel load and topography affected the likelihood of containment.

**Figure 5.3.** Conceptual model describing the process for house loss from wildfires. Black rectangles represent sub-models of the Bayesian Network. Circles represent the drivers of fire behaviour. White rectangles represent management treatments.

5.3.3 Model development

A Bayesian Network model was developed to include the three sub-models in the conceptual model (Fig. 5.3) and the relevant environmental and human variables. The three treatment options, ignition management, suppression and fuel management, were included in the Network as decision nodes. The overall structure of the Network is illustrated in Figure 5.4. Node definitions are available in Appendix D Table D1. The Bayesian Network model was constructed using Netica software (Norsys Software Corp., Vancouver, BC, Canada).
Figure 5.4  Bayesian Network for the likelihood of house loss. The top tier of nodes in the diagram represent the likelihood of ignition, the middle tier of nodes represent the likelihood of containment and the bottom tier of nodes represent the likelihood of house loss. Nodes are described in Appendix D Table D1.

The likelihood of ignitions caused by lightning, arson, powerline faults/failures and other accidental human-caused sources (e.g. escapes from prescribed burns, fires caused by equipment or machinery use) were incorporated into the Network based on models developed by Clarke et al. (in review) for wildfire ignitions in Victoria, Australia. These models were derived from maximum entropy algorithms that iteratively contrasted environmental and human variables at ignition locations (12 years of ignition data) against those of a large sample of random locations. These models were considered appropriate to use as the results largely conform to previous research undertaken in the Sydney Basin bioregion which only included arson and lightning ignitions (Penman et al. 2013b). The variables chosen for the ignition sub-models were based on the Victoria-wide model for each ignition type. For arson, powerline and other accidental human-caused ignitions, the model inputs were distance to roads, house density and forest fire danger index (FFDI). The FFDI is related to the chance of a fire igniting, its rate of spread
and difficulty of suppression and is calculated using wind speed, relative humidity, temperature, recent rainfall and a long term drought variable (Noble et al. 1980). For lightning ignitions, the model inputs were the annual rainfall, distance to roads and FFDI.

There were five levels of ignition management considered in the decision node ‘Ignition Management’: the current programme, and increased effort to reduce arson and powerline ignitions each independently by 10 or 20%. An increased effort to reduce arson could involve activities such as education programmes aimed at preventing deliberate fire lighting, arson intervention programmes targeting known offenders, limiting access to areas of flammable vegetation and increasing patrols of these areas on days of very high fire danger (Muller 2009). The increased effort to reduce powerline ignitions could include burying cables underground in high risk areas, installing devices that automatically switch off power or rapidly reduce the current when a fault occurs, changing settings on high fire risk days to reduce energy release if a fault occurs and vegetation management around powerlines (Mitchell 2013).

The likelihood of containment for grass and forest fires were based on random forest models developed by Collins et al. (2018) for wildfires in NSW. Separate models were used for grass and forest fires. For forest fires, the probability of containment within 4 hours of suppression crews arriving at the fireground was modelled using FFDI, response time, the number of tankers per ha of fire, fuel load, slope and whether aircraft were deployed to suppress the wildfire. For grass fires, the probability of containment within 2 hours of suppression crews arriving at the fireground was modelled using the same variables as for forest fires except the fuel load was given a constant value. Although fuel load affects suppression difficulty in grass fires due to its influence on flame height, flame depth and fire intensity (Cheney and Sullivan 2008), it was not included as a variable in the grass containment model as fine scale variation in grass fire loads is a function of stocking rates (grazing) and antecedent rainfall (Cheney and Sullivan 2008) for which data is not available statewide. We assumed the fuel load was a constant 4.5 t/ha which is the expected fuel load from a good growing season in undisturbed pastures (Luke and McArthur 1978) and therefore represents maximum risk. The containment model variables were chosen based on their variable importance.
There were five levels of suppression management considered in the decision node ‘Suppression’: current resources; 20% more tankers per ha of fire; 20% less tankers per ha of fire; response time decreased by 20%; and response time increased by 20%.

There were five levels of fuel management considered in the decision node ‘Fuel management’: no prescribed burning treatment; the current programme for each bioregion; and increased prescribed burning effort by an additional 1, 2 and 5% of treatable area per annum. The prescribed burning treatment option was only applied to the bioregions with forest fires as grass fuels are rarely managed by prescribed burning due to the rapid (<1yr) return to pre-burn levels.

The likelihood of house loss was modelled using FFDI and ignition type based on data on houses destroyed by wildfires over a 12 year period in Victoria and NSW (Collins et al. 2016). A house was considered to be destroyed by a wildfire if the likelihood of house loss by ignition type was moderate or high.

5.3.4 Data to populate the conditional probability tables

Data used to populate the conditional probability tables were derived from either measured data specific for each bioregion in the study area or the models described above. Bioregions were included in the study if they had >100 grass or forest fire incidents in the containment data from Collins et al. (2018) (Appendix D Table D1). There were 5 bioregions for forest fires and 11 bioregions for grass fires.

Spatial data were used to calculate distance to roads, house density, slope, vegetation type and fuel load for each bioregion. Distance to roads was calculated by measuring the shortest distance to the nearest mapped road (data source NSW Land and Property Information) or fire trail (data source NSW Rural Fire Service). House density was measured by calculating the number of houses within a 2km radius from address point locations sourced from NSW Land and Property Information. Slope was calculated from a 30m digital elevation model sourced from Geoscience Australia. Vegetation type was categorised into three major types: forest, grassland, and nonfuel, from a fuel type data layer provided by the NSW Rural Fire Service. The forest category included forest, woodland and heath. The grassland category included grasslands, chenopod and crops. The nonfuel category included urban, water, sand and no vegetation. The current fuel load
was calculated from predicted fuel load data provided by the NSW Rural Fire Service based on vegetation class (Keith 2004), fire history and fuel accumulation relationships (Horsey and Watson 2012; Watson et al. 2012; Gordon and Price 2015). To calculate the fuel loads for the fuel management strategies, we took the current fuel load and adjusted it depending on the treatment. The current programme of prescribed burning was determined for each bioregion by calculating the mean annual hectares treated over a 5-year period from 2012/13 to 2016/17 (NSW Rural Fire Service data) and dividing by the area of forest vegetation in the bioregion. The Sydney Basin bioregion had the highest mean % forest area treated by prescribed burning annually, 1.84%, and South East Queensland had the lowest, 0.30% (Appendix D Table D2). The fuel load for the no prescribed burning treatment was calculated by increasing the current fuel load for each vegetation class by the annual % prescribed burning for the bioregion unless the fuel load was currently at its maximum limit. This was done for all vegetation classes except those where prescribed burning is not permitted as per the Bush Fire Environmental Assessment Code (https://www.rfs.nsw.gov.au/resources/publications/hazard-reduction/bush-fire-environmental-assessment-code) e.g. rainforests, alpine forests, saline wetlands. For the increased prescribed burning effort treatments, the vegetation class and fuel accumulation relationships were used to calculate the reduction in fuel load for each vegetation class at the relevant treatment level. The current fuel loads for each vegetation class were then adjusted by the reduction in fuel load. For example, a 2% increase in prescribed burning for Sydney Coastal Dry Sclerophyll forests results in an 9.9% reduction in fuel load, so the current fuel load for this vegetation class were reduced by this amount.

Mean annual probability distributions of FFDI and rainfall were calculated from weather data sourced from the Bureau of Meteorology. The FFDI was calculated from the 1500 h daily weather for all weather stations for the years 1982 – 2013 using the formula in Noble et al. (1980). For the New England Tablelands bioregion the extreme and catastrophic categories were zero because the maximum FFDI was in the severe category for this bioregion. Mean annual rainfall was calculated from daily gridded (0.5° x 0.5°, approx. 5 km by 5 km) rainfall data for the years 1990 – 2011.

The data for the ‘Arson’, ‘Powerline’, ‘Other’ and ‘Lightning’ nodes were derived by categorising the results data (probability of ignition) from the maximum entropy algorithms (Clarke et al. in review) for each ignition model and the relevant model
variables and determining the proportion of results within each ignition likelihood category for each combination of predictor variables. For the other accidental human-caused ignition sub-model, the maximum probability of accidental, accidental relating to machinery or vehicles and escaped fire from prescribed burns was used. To calculate the ignition management treatments the probability of ignition data from the maximum entropy algorithms for arson and powerlines were reduced by 10 or 20% and the proportion of results within each ignition likelihood category recalculated.

The data for ‘Response Time’, ‘Tankers’ and ‘Aircraft’ nodes were calculated for each bioregion using the fire incident response data from Collins et al. (2018). The ‘Response Time’ node and ‘Tankers’ node data were either increased or decreased by 20% for the relevant suppression treatment. The data for the ‘Arson Contained’, ‘Powerline Contained’, ‘Other Contained’ and ‘Lightning Contained’ nodes were calculated from the random forest model generated using the chosen variables and data from Collins et al. (2018) with the predictor variable being whether the fire was contained within 2 or 4 hours.

The data for ‘Arson House Loss’, ‘Powerline House’, ‘Other House Loss’ and ‘Lightning House Loss’ nodes was calculated from the proportion of ignitions that resulted in house losses by ignition type and FFDI category i.e. for each ignition type and FFDI category, the number of ignitions that resulted in house losses divided by the total number of ignitions in the 12-year period. This data was then combined with the likelihood of ignition type contained to determine the likelihood of house loss by ignition type and then the all house loss calculated.

5.3.5 Scenario testing

The base scenario for the annual risk of house loss for each bioregion was determined by setting the node ‘Bioregion’ to the specified bioregion, the node ‘Vegetation’ to forest or grass and setting the decision nodes ‘Ignition Management’ to current programme, ‘Suppression’ to current resources and ‘Fuel Management’ to current practice. Then each of the choices in the decision nodes were run producing 125 management scenarios (5 ignition management x 5 suppression x 5 fuel management) for forest fires and 25 management scenarios (5 ignition management x 5 suppression) for grass fires. Comparisons between the management scenarios were made using the likelihood of
house loss from the node ‘All House Loss’. To examine the impact of management we calculated the % difference from the base scenario i.e. the current strategy for each bioregion.

To examine the effectiveness of management scenarios when the FFDI > 50, the node ‘Fire Danger Index’ was adjusted by setting the likelihood of FFDI < 50 categories to 0 and the likelihood of FFDI > 50 categories to 1. All management scenarios (including the base scenario) for both forest and grass fires were re-ran for each bioregion.

5.3.6 Sensitivity analysis

A sensitivity to findings analysis was undertaken using the Bayesian Network without the decision nodes as this type of analysis cannot be performed on decision Networks in Netica. The sensitivity to findings analysis determines which variables have the greatest influence on the target node i.e. all house loss. The sensitivity of findings was calculated using the mutual information metric with the chance nodes set to their default prior probability distributions. Mutual information measures the amount of information shared between the target node and each of the chance nodes, it quantifies the extent to which each node reduces uncertainty (entropy) on the target node, if the value is 0 the nodes are considered independent (Korb and Nicholson 2004; Marcot 2012).

5.4 Results

5.4.1 Forest fires

The annual risk of house loss from forest fires for the base scenario ranged from 0.013 for Sydney Basin and NSW North Coast to 0.018 for South Eastern Highlands i.e. for the South Eastern Highlands bioregion there is a 1.8% chance that a forest fire will destroy at least one house annually. The greatest reduction in annual risk of house loss from forest fires from treatment strategies ranged from 15% for NSW North Coast to 32% for NSW South Western Slopes (Fig. 5.5). The treatment combination that resulted in the greatest reduction in annual risk of house loss for all bioregions was 20% more tankers per ha of fire, 20% reduction in powerline ignitions and 5% increase in prescribed burn effort. The best individual treatment for all bioregions was 20% more tankers per ha of fire which reduced the annual risk of house loss by 8 – 18%. Reducing the powerline ignitions by 20% was the next best treatment resulting in a 5 – 11% reduction in house loss risk.
Increasing the prescribed burning effort had the greatest reduction on the annual risk of house loss in the NSW South Western Slopes bioregion (5% reduction for the 5% prescribed burning effort) but generally had minimal effect (0 – 1% reduction) in the other bioregions. Decreasing the arson ignitions by 20% resulted in a 1 – 2% reduction in house loss risk. Decreasing and increasing the response time resulted in a 1% reduction or increase in house loss risk. Reducing the number of tankers per ha of fire resulted in a 2 - 4% increase in house loss risk.

**Figure 5.5** The % change in probability of house loss for forest fires from the current ignition management, fuel management and resource availability using combinations of treatment strategies for each bioregion. NNC = NSW North Coast, NSS = NSW South Western Slopes, SB = Sydney Basin, SEH = South Eastern Highlands, SEQ = South Eastern Queensland. PB = Prescribed burning effort. Symbol type represents ignition management effort □ = no additional programme, ● = 10% arson reduction, ▽ = 20% arson reduction, ■ = 10% powerline reduction, ○ = 20% powerline reduction
When the FFDI > 50, the risk of house loss from forest fires for the base scenario ranged from 0.69 for NSW South Western Slopes to 0.90 for South Eastern Queensland. The greatest reduction in risk of house loss when the FFDI > 50 from treatment strategies ranged from 10% for NSW North Coast to 26% for NSW South Western Slopes (Fig. 5.6). The treatment combination that resulted in the greatest reduction in risk of house loss for all bioregions when the FFDI > 50 was the same as the all FFDI scenarios i.e. 20% more tankers per ha of fire, 20% reduction in powerline ignitions and 5% increase in prescribed burn effort. The best individual treatment for all bioregions except South Eastern Queensland was 20% more tankers per ha of fire which reduced the risk of house loss by 5 – 13%. Reducing the powerline ignitions by 20% was the best treatment for South Eastern Queensland and the second best treatment for all other bioregions resulting in a 4 – 9% reduction in house loss risk. Similar to the all FFDI scenarios, increasing the prescribed burning effort was most effective in the NSW South Western Slopes bioregion (4% reduction for the 5% prescribed burning effort) but generally had minimal effect (0 – 1% reduction) in the other bioregions. Decreasing the arson ignitions by 20% had minimal effect < 1% reduction in house loss risk in all bioregions. Likewise, decreasing and increasing the response time also had a minimal effect < 1% reduction or increase in house loss risk for all bioregions. Reducing the number of tankers per ha of fire resulted in a 1 - 2% increase in house loss risk.
Figure 5.6 The % change in probability of house loss for forest fires from the current ignition management, fuel management and resource availability when the forest fire danger index > 50 using combinations of treatment strategies for each bioregion. NNC = NSW North Coast, NSS = NSW South Western Slopes, SB = Sydney Basin, SEH = South Eastern Highlands, SEQ = South Eastern Queensland. PB = Prescribed burning effort. Symbol type represents ignition management effort □ = no additional programme, ● = 10% arson reduction, ▽ = 20% arson reduction, ■ = 10% powerline reduction, ○ = 20% powerline reduction.

5.4.2 Grass fires

The annual risk of house loss from grass fires ranged from 0.00008 for New England Tablelands to 0.0059 for South Eastern Highlands. The annual risk for the New England Tablelands bioregion is very low as the maximum FFDI is within the severe category for this bioregion whereas all other bioregions have recorded FFDI in the extreme and catastrophic categories. The reduction in annual risk of house loss from grass fires from mitigation treatments ranged from 30% for Nandewar and South Eastern Highlands to
61% for New England Tablelands bioregion (Fig. 5.7). The treatment combination which resulted in the greatest reduction in annual risk of house loss for all bioregions was 20% reduction in powerline ignitions and 20% more tankers per ha of fire. The best individual treatment that produced the greatest reduction in the annual risk of house loss from grass fires for all bioregions was 20% more tankers per ha of fire which reduced the annual risk of house loss by 20 – 39%. Reducing the powerline ignitions by 20% was the second best treatment for all bioregions resulting in a 8 – 36% reduction in house loss risk, followed by 20% faster response time which reduced the annual risk of house loss by 3 – 13%. Reducing the arson ignitions by 20% had a small effect, reducing the annual risk of house loss by <2%. Increasing the response time by 20% resulted in an increase in annual house loss risk by 4 – 12%. Reducing the number of tankers per ha of fire by 20% resulted in a 0 – 12% increase in house loss risk.

When the FFDI > 50, the risk of house loss from grass fires ranged from 0.030 for New England Tablelands to 0.46 for South Eastern Queensland. The reduction in risk of house when the FFDI > 50 from mitigation treatments ranged from 27% for Nandewar and South Eastern Highlands to 68% for New England Tablelands bioregion (Fig. 5.8). The treatment combination which resulted in the greatest reduction in risk of house loss for all bioregions when the FFDI > 50 was the same as the all FFDI scenarios i.e. 20% reduction in powerline ignitions and 20% more tankers per ha of fire (Fig. 8). The best individual treatment that produced the greatest reduction in risk of house loss for all bioregions was 20% more tankers per ha of fire which reduced the risk of house loss by 17 – 46%. Reducing the powerline ignitions by 20% was the second best treatment resulting in a 6 – 12% reduction in house loss risk for all bioregions except New England Tablelands where a 41% reduction resulted. Decreasing the response time by 20% reduced the risk of house loss by 3 – 11%. Reducing the arson ignitions by 20% reduced the risk of house loss by <2%. Increasing the response time by 20% resulted in an increase in house loss risk by 4 – 9%. Reducing the number of tankers per ha of fire by 20% resulted in a 1 – 6% increase in house loss risk.
**Figure 5.7** The % change in probability of house loss for grass fires from the current ignition management and resource availability using combinations of treatment strategies for each bioregion. BBS = Brigalow Belt South, CP = Cobar Peneplain, DRP = Darling Riverine Plain, NAN = Nandewar, NET = New England Tablelands, NNC = NSW North Coast, RIV = Riverina, SB = Sydney Basin, SEH = South Eastern Highlands, SEQ = South Eastern Queensland, NSS = NSW South Western Slopes. Symbol type represents ignition management effort $\square$ = no additional programme, $\bullet$ = 10% arson reduction, $\triangledown$ = 20% arson reduction, $\blacksquare$ = 10% powerline reduction, $\circ$ = 20% powerline reduction.
Figure 5.8 The % change in probability of house loss for grass fires from the current ignition management and resource availability when the forest fire danger index > 50 using combinations of treatment strategies for each bioregion. BBS = Brigalow Belt South, CP = Cobar Peneplain, DRP = Darling Riverine Plain, NAN = Nandewar, NET = New England Tablelands, NNC = NSW North Coast, NSS = NSW South Western Slopes, RIV = Riverina, SB = Sydney Basin, SEH = South Eastern Highlands, SEQ = South Eastern Queensland. Symbol type represents ignition management effort ☐ = no additional programme, ● = 10% arson reduction, ▽ = 20% arson reduction, ■ = 10% powerline reduction, ○ = 20% powerline reduction.

5.4.3 Sensitivity analysis
The sensitivity analysis showed that the ‘Powerline House Loss’ node had the greatest influence on the probability of house loss followed by the ‘Fire Danger Index’ node (Fig. 5.9). This is expected as nodes that are closest to the target node are likely to have a high amount of shared information. For the variables beyond the immediate parent nodes of the ‘All House Loss’ node, the ‘Powerline’ and ‘Lightning’ nodes rank highly in the
model. The least influential nodes (<1% shared information) were ‘Tankers’, ‘Distance to Road’, ‘Response Time’, ‘Aircraft’, ‘Annual Rainfall’, ‘House Density’ and ‘Slope’. This suggests that FFDI has a strong influence on the likelihood of powerline and lightning ignitions as the other variables that determine the likelihood of ignition had very low influence.

Figure 5.9  Sensitivity to findings in the Bayesian Network to the All House Loss node

5.5  Discussion

The annual risk of house losses was 3 or 4 times higher for forest fires than grass fires which aligns with previous findings on house losses in NSW and Victoria where 85% of houses destroyed were from forest fires (Collins et al. 2016). Mitigation treatments reduced the annual risk of house losses from grass fires by 30 - 61% and by 15 - 32% from forest fires. Increasing the number of tankers per ha of fire and reducing the powerline ignitions by 20% were the most effective treatments for all fires and increasing the prescribed burning effort had minimal effect on forest fires. The risk of house losses
increased for both forest and grass fires when the FFDI > 50 and the effectiveness of mitigation treatments decreased for forest fires. This finding concurs with previous studies that most house losses in Australia occur when the FFDI > 50 (Blanchi et al. 2010) and mitigation treatments are less effective under severe fire weather conditions (Price and Bradstock 2012; Penman et al. 2013c).

The suppression treatments were more effective for grass fires than forest fires at higher FFDI due to differences in accessibility to the fire and suppression tactics. Tankers can usually access (drive directly to) the fire perimeter of a grass fire but are constrained to available roads for forest fires. This in turn affects whether fire suppression can be directly achieved using hand crews or machinery. The upper fire intensity threshold for direct attack by a hand crew is 350 - 500 kW/m (Hirsch and Martell 1996) and around 2000 kW/m for ground-based crews in Australian eucalypt forests (Loane and Gould 1986), although the threshold limit for tankers is unknown. In dry eucalypt forests, firefighters are generally unable to suppress fires with a head fire intensity > 1000 kW/m due to the number of spot fires occurring across the control line (Budd et al 1997). As the FFDI increases, the head fire intensity increases to well beyond the thresholds for direct suppression of a fire. For example, head fire intensity estimates for crown fires in most eucalypt forests range from 7000 – 70000 kW/m (Cheney 1981) and under catastrophic FFDI head fire intensities ranged from 70000 - 88000 kW/m with prolific short range (< 1km) spotting and long range (> 5km) spotting (Cruz et al. 2012). The head fire intensity of a very fast grass fire can be up to 60000 kW/m (Cheney and Sullivan 2008) which would also be unable to be attacked directly. However, in these situations, direct suppression attack starts from the rear where the intensity is much lower (Catchpole et al. 1982) and progresses along the flanks towards the fire head (Luke and McArthur 1978; Cheney and Sullivan 2008).

Suppression treatments were more effective at reducing house loss risk than both ignition management and fuel management. Our results showed that increasing the suppression resources was more effective than a faster response which is in contrast to a simulation study in Sydney Basin bioregion (Penman et al. 2013c) who found the opposite effect. This contrast was most likely due to how the response times were estimated with response times estimated from fire ignition in Penman et al. (2013c) and from time since the fire was reported (the time of ignition was unknown) in this study. The response time classes
in Penman et al. (2013c) of 1, 2 and 4 hours from fire ignition were slower than the classes in this study (Appendix D Table D1) based on the time since the fire was reported. For ignitions occurring close to populated areas, the time from ignition to the fire being reported is likely to be short, particularly on days of high FFDI, as the public are requested to report all unattended fires and firefighters are ready (stood up) at brigade stations in anticipation of fire activity. In these cases, a minimum response time of an hour is likely to be an overestimate of the true time. However, for ignitions occurring away from populated areas, the time from ignition to the fire being reported may be considerable if no active fire detection systems (e.g. fire towers, reconnaissance planes, drones) are in place. In these cases, a larger proportion of the data would be expected to be in the slowest response time category particularly since the travel distance from the station to the fire is likely to be much greater in rural areas than urban areas.

Increasing the number of tankers may be very difficult in large parts of NSW where the vast majority of available firefighters are volunteers (McLennan and Birch 2005). In remote rural areas there may be insufficient firefighters to man additional tankers. The number of volunteer firefighters in these areas has been declining and the age profile of volunteers increasing as people, particularly those aged 18-35 years, have shifted away from smaller rural communities to larger regional centres and urban areas for greater employment opportunities (McLennan and Birch 2005; Parkin 2008). In areas near the wildland-urban interface, where potential volunteer numbers are higher, it may be difficult to assemble additional firefighting crews during business hours as volunteers are at their work places away, often some considerable distance, from their local community (McLennan and Birch 2005). There has also been a shift in the way people volunteer from the traditional long-term commitment style of volunteering which firefighting agencies rely heavily on, to a more diverse and short term episodic style of volunteering where there is greater individual choice on where, how and why people volunteer (McLennan et al. 2016). If this trend continues, the fire agencies may struggle to attract volunteers who are prepared to volunteer their time over a period of years which is generally preferred given the time and money invested to train volunteers for firefighting roles (McLennan and Birch 2005).

Alternatively, additional crews could be formed using salaried firefighters but this would impose significant additional costs that communities may find difficult to justify (Birch
and McLennan 2007). There would also be the cost of purchasing and maintaining the additional tankers, a new tanker (category 1) costs $300000 (NSW Rural Fire Service data). Alternately, additional resources could be achieved by a more fluid national response approach where tankers are shifted between States depending on the fire season. This type of approach is currently used for aircraft but may not be practical for tankers as most agency’s tankers are designed specifically to suit their local conditions. In addition, if the tankers are manned by out of area crews, then the lack of local knowledge may result in less effective use of resources. It also may not be possible because fire seasons are extending, with an earlier start to the fire season in southern Australia and a later finish in northern Australia (Dowdy 2018).

Reducing the number of powerline ignitions was a more effective ignition management treatment than reducing the number of arson ignitions. Although the number of powerline-caused wildfires is much lower than the number of arson ignitions, powerline-caused fires are disproportionally higher for wildfires that result in house losses (Collins et al. 2016). The proportion of powerline-caused fires relative to all wildfire causes increases at FFDI > 50 (Mitchell 2013; Miller et al. 2017) whereas the proportion of arson-caused fires decreases (Miller et al. 2017). Powerlines can cause wildfires by wires clashing, animals, trees or branches contacting wires, and stress failures where a component of the powerline breaks e.g. wires, poles, cross-arms, insulators (Powerline Bushfire Safety Taskforce 2011; Mitchell 2013). Automatic circuit reclosers were identified as a contributing factor in several major fires in California and Victoria (Teague et al. 2010; Mitchell 2013). These devices turn off the powerline when a fault occurs and after a period of time, they try to restore the power. However, in trying to restore the power, the energy release from the reclose attempt can result in a higher probability of wildfire ignition than the initial fault (Coldham et al. 2011). Remotely controllable automatic circuit reclosers allow the settings to be adjusted on high fire risk days and the number of reclose attempts can be modified or disabled entirely (Powerline Bushfire Safety Taskforce 2011; Mitchell 2013). This reduces the likelihood of a reclose attempt causing a wildfire but the initial fault may still ignite a wildfire. A rapid earth fault current limiter is a device to rapidly limit energy release from a wire-to-earth fault and wire touching or into vegetation fault (Powerline Bushfire Safety Taskforce 2011; Marxsen 2016). By reducing fault currents to very low levels within milliseconds of the fault
occurring powerline-caused ignitions may be reduced by 90% for these types of faults (Marxsen 2016). The costs of installing these devices and ancillary works at zone substations ranges from $1 million to $9 million per zone substation (Powerline Bushfire Safety Taskforce 2011). There are over 800 zone substations in NSW ($0.8 - $7.2 billion) but the installation of rapid earth fault current limiters could be prioritised to areas of highest wildfire risk. However, faults that occur because of a branch-across-wires fault where the branch is fully detached from the tree and is suspended above ground cannot be reduced by these devices so burying cables or using covered conductors to replace bare overhead wire would be required to reduce this type of fault (Marxsen 2016). The cost would be at least $40 billion for underground cables and $20 billion for covered cables (Powerline Bushfire Safety Taskforce 2011).

Prescribed burning was the least effective mitigation treatment for reducing house losses from forest fires. Several previous studies have also found that prescribed burning has a limited influence on the area burned (Cary et al. 2009; Penman et al. 2011b; Price et al. 2015b). Fuel treatments at the wildland-urban interface have be found to be more effective at reducing house losses than landscape treatments (Stockmann et al. 2010; Bradstock et al. 2012; Gibbons et al. 2012; Penman et al. 2014a). In our study we did not specify where the increased prescribed burning effort was applied within the bioregion which may have reduced the effectiveness of the treatment. A study by Bradstock et al. (1998) found that 40% of the wildland-urban interface would need to be burnt each year to minimise the risk of uncontrollable fire in northern Sydney. This amount of prescribed burning is not likely to be achievable given the low annual % area prescribed burnt currently and the lack of suitable weather windows to ensure burns do not escape their proposed boundaries (Penman et al. 2011a). There is also likely to be adverse health impacts, including premature deaths from the smoke produced (Broome et al. 2016; Williamson et al. 2016; Horsley et al. 2018) and negative biodiversity effects (Bradstock et al. 1998; Penman et al. 2011a).

It is not possible to stop all fires from reaching the wildland-urban interface regardless of the mitigation treatments applied (Syphard et al. 2011; Penman et al. 2013c; Calkin et al. 2014). There are a range of other mitigation measures that could reduce the susceptibility of homes to wildfire that were not included in the study. Many countries implement land use planning and building development measures to determine where and how houses are
built in wildfire-prone areas (e.g. Buxton et al. 2011; Galiana-Martin 2017; Kocher and Butsic 2017) but these arrangements are typically not retrospective so other measures are required for existing housing. For example, retrofitting houses to reduce radiant heat and ember penetration (Penman et al. 2017; Kalhor and Valentin 2018), vegetation management around the house to reduce radiant heat and flame exposure (e.g. Moritz et al. 2014; Syphard et al. 2014; Gibbons et al. 2018) and encouraging residents to prepare their houses for protection from wildfire (Penman et al. 2013a; Penman et al. 2016; Kramer et al. 2018).

In constructing the model of likelihood of house loss we assumed that if a grass or forest fire was not contained within 2 or 4 hours then it could potentially cause a house loss. This assumption may overestimate house losses from these fires as depending on where the fire started, it may have been possible to contain these fires before they impacted properties. This is most likely the case for lightning-caused fires as these ignitions typically occur away from population centres (e.g. Narayanaraj and Wimberly 2012; Penman et al. 2013b) and when lightning-caused fires have resulted house losses only 22% have occurred on the day of ignition (Collins et al. 2016). An underlying assumption of the containment model was that all resources were used to contain the fire (Collins et al. 2018) but not to protect houses or any house based strategies to minimise house loss. The Bayesian Network model could be expanded to include house-based strategies and consider management strategies at various scales e.g. landscape and local strategies (Penman et al. 2014a). Despite these assumptions and limitations, the model is still useful to compare the relative effects of the mitigation strategies.

5.6 Conclusion

The treatment combination that resulted in the greatest reduction in annual risk of house losses from wildfires was 20% more tankers per ha of fire and 20% reduction in powerline ignitions, with the addition of 5% increase in prescribed burning effort also effective for forest fires. When the FFDI > 50, the risk of house losses increased for both forest and grass fires and the effectiveness of mitigation and suppression treatments decreased for forest fires. However, given agencies have limited budgets to implement fire mitigation and suppression programmes, a cost benefit analysis of treatment options is required to inform investment decisions. Future research could also include developing a spatially explicit model and extending the model to include mitigation strategies at the wildland-
urban interface. For example, community engagement activities to improve how residents prepare for wildfires and building design to reduce radiant heat and ember penetration.

5.7 Acknowledgements
Data for the analysis were provided by the NSW Rural Fire Service.
Chapter 6

6 RESEARCH SYNTHESIS

Wildfires can have devastating consequences for human life, property and the environment. Therefore, fire and land managers aim to implement management actions which reduce or modify the wildfire risk to assets. However, what is often lacking when undertaking wildfire risk analyses is a quantification of the effectiveness of risk treatment strategies and information to better design prevention strategies. Prevention treatments seek to eliminate or reduce the impact of wildfires and/or to reduce the vulnerability of assets to the impacts of wildfires. Response strategies seek to contain wildfires with a potential to cause damage to life, property and the environment.

This thesis attempted to examine the drivers of ignitions, which ignitions pose more risk, and the factors that influence the containment of wildfires to better design prevention and response strategies and to investigate the effectiveness of these treatments. The present chapter summarises the key findings of the study relating to the spatial patterns of wildfire ignitions (6.1), the relationship between wildfire ignition causes and destroyed houses (6.2), the dominant influences on the containment of wildfires (6.3), and the relative influence of mitigation and response strategies on annual house loss risk (6.4), followed by a discussion on future research (6.5).

6.1 Spatial patterns of wildfire ignitions

The spatial patterns of wildfire ignitions in south-eastern Australia was found to be driven by population density. This was consistent with expectations, given that 87% of ignitions with a known cause in the study area are due to humans, and accords with results from elsewhere in Australia (Bryant 2008a), and from California (Syphard et al. 2007), Canada (Gralewicz et al. 2012) and south-western Europe (Oliveira et al. 2014). The number of accidental and deliberate ignitions increased with increasing population density and decreasing mean elevation (Table 2.4). This is consistent with previous studies on deliberate ignitions where arsonists were more likely to light fires in easily accessible areas, close to roads and population centres (Bryant 2008a; Reineking et al. 2010; Penman et al. 2013b; Serra et al. 2014). Lightning ignition probability increased as the number of
hot days and mean elevation decreased which reflects that fewer lightning ignitions occurred in the western arid and semiarid areas (Fig. 2.5 & Appendix A. Fig. A1). This is in contrast with results from previous studies in the Sydney Basin bioregion (Penman et al. 2013b) and other countries (Podur et al. 2003; Krawchuk et al. 2006; Wu et al. 2014; Yang et al. 2015) that reported that lightning-caused fires were more likely to occur in high-elevation areas. Our result may be due to a scale effect whereby the coarse spatial resolution used for this study may be masking finer scale relationships such as topographic position (Parisien et al. 2014).

More ignitions are expected in the coastal and hinterland areas in future years due to population increases and climate change effects. The fastest rates of population growth outside of capital cities in Australia is predicted to occur in the peri-urban and coastal regions (McGuirk and Argent 2011). An increase in temperature and reduced rainfall is predicted for the eastern and southern regions of the study area (Clarke et al. 2011). This is likely to reduce fuel moisture and increase fuel ignitability and the proportion of fuel available to burn, particularly in regions dominated by forests in the coastal and hinterland areas (Appendix A Fig. A2). This suggests that more ignitions are likely in these areas, increasing the wildfire risk to people and property. Urban development patterns need to be designed so that they are not a driver of vulnerability to wildfire risk (Syphard et al. 2013). Land use planning and building design policies that include wildfire protection measures are likely to be important mitigation treatments for reducing wildfire risk to people and property.

6.2 Wildfire ignitions that destroyed houses

The main ignition causes of wildfires that destroyed houses in south-eastern Australia were powerlines, lightning strikes and deliberate ignitions (Table 3.2). Fire weather was an important driver for deliberate- and powerline-caused wildfires that destroyed houses with temperature, wind speed and FFDI all significantly higher and RH significantly lower ($P < 0.05$) on the day of ignition for wildfires that destroyed houses compared with wildfires where no houses were destroyed (Fig. 3.4). This supports the findings of other studies that fire weather is the dominant factor that determines the probability of wildfires destroying houses (Gibbons et al. 2012; Price and Bradstock 2012; Penman et al. 2014a; Penman et al. 2014b). For lightning-caused wildfires wind speed was significantly higher
on the day of ignition for wildfires that destroyed houses compared with wildfires where no houses were destroyed (Fig. 3.4). However, for most lightning-caused wildfires (59%) the first destroyed house occurred at least two days after the fire started whereas for all powerline-caused wildfires the first house was destroyed on the day the fire started and for deliberate-caused wildfires the first house destroyed most often occurred (85%) on the day the fire started (Table 3.4). These results are consistent with previous research that weather and proximity to houses are important factors for the probability of house loss (Penman et al. 2013c; Price and Bradstock 2013).

Powerline- and lightning-caused fires pose a higher risk of destroying houses than deliberately ignited wildfires. The proportion of deliberately ignited wildfires that destroyed houses is only slightly higher than the proportion of deliberately ignited wildfires where no houses were destroyed whereas powerlines were 6 times more common in the wildfires that destroyed houses data than in the wildfires where no houses were destroyed data and lightning was 2 times more common (Fig 3.6). This finding has been supported by more recent research by (Miller et al. 2017) who found the proportion of powerline-caused fires relative to all wildfire causes increases at FFDI > 50.

To decrease the number of wildfires that destroy houses, efforts should be focussed on improving the safety of powerlines, reducing the potential for fire spread of lightning-caused wildfires and reducing the number of deliberate wildfire ignitions. New technologies and operational practices can reduce powerline ignitions but this requires substantial expenditure to achieve this outcome (Powerline Bushfire Safety Taskforce 2011) and it is not feasible to prevent all ignitions (Marxsen 2016). Arson prevention programmes and other measures may reduce the number of deliberate ignitions but arsonists are rarely caught (Muller 2009; Landsell et al. 2011) and there will always be some people who choose to light wildfires (Willis 2005). Fuel reduction treatments may reduce fire spread but the level of treatment required in the landscape to substantially alter the risk of wildfires destroying houses is very large (Bradstock et al. 2012) and is likely to result in substantial environmental impacts (Furlaud et al. 2018). Inevitably, this means that it is impossible to stop all wildfires from reaching houses and mitigation treatments around houses is also required to reduce the number of houses destroyed by wildfires.
6.3 Factors that influence wildfire containment

It is clearly unrealistic to remove ignitions from the landscape; therefore consideration needs to be given to the extent to which going fires can be contained before they damage assets. The dominant influences on the containment of both forest and grass fires were the number of resources per ha of fire and fire weather conditions (Fig. 4.3). This result is consistent with other studies that found increasing crew size increased the probability of containment (Hirsch et al. 2004; McCarthy et al. 2012) and reduced average fire area (Podur and Martell 2007; Penman et al. 2013c) and the probability of containment decreases as fire weather severity increases (Arienti et al. 2006; Plucinski 2012; Penman et al. 2013c; Plucinski 2013). Fuel load and slope also had a strong negative influence on the probability of containment of forest fires and has been reported in other studies (McCarthy et al. 2012; Plucinski 2012). Slope and response time had only a minor influence on the probability of containment of grass fires which has also been reported by Plucinski (2013).

Opportunities for fire managers to influence the probability of containment of wildfires are limited to modifying the number of resources available, the location of these resources and/or the fuel load. Fuel reduction treatments may assist fire suppression efforts but to be effective, a wildfire must encounter a treated patch while in a fuel reduced state and under weather conditions that will allow suppression resources to contain the fire (Price and Bradstock 2010, 2012). When wildfires are mostly weather-dominated (forest danger index > 50), suppression is only likely to be successful when the wildfire is still developing and small (Tolhurst and McCarthy 2016). Targeting fuel treatments and locating resources to areas where fire ignitions are predicted to occur may be effective in improving the probability of fire containment. For human-caused ignitions this is most likely to be close to population centres and roads (e.g. Syphard et al. 2008; Narayanaraj and Wimberly 2012; Penman et al. 2013b; Collins et al. 2015).

6.4 Effectiveness of mitigation strategies to reduce house loss risk

Across forest and grass ecosystems a 20% increase in tankers per ha of fire, followed by 20% reduction in powerline ignitions produced the greatest reduction in annual house loss risk (Fig 5.5 & 5.7). Increasing the prescribed burning effort was the least effective
treatment for reducing house loss from forest fires (0 – 1% reduction for all bioregions except for NSW South Western Slopes which had a 2 – 5% reduction). The risk of house losses increased and the effectiveness of mitigation and suppression treatments decreased when the FFDI > 50 (Fig 5.6 & 5.8). These findings were consistent with expectations, as previous studies have shown most house losses in Australia occur when the FFDI > 50 (Blanchi et al. 2010) and mitigation treatments are less effective under severe fire weather conditions (Price and Bradstock 2012; Penman et al. 2013c).

Increasing the number of suppression resources available may not be possible or practicable given the financial cost involved in tanker purchase, recruitment and training of firefighters and the extra burden this may place of volunteer firefighters. Investing in preventing powerline ignitions should be considered further as this was the ignition cause with the highest likelihood of house loss for both forest and grass fires. As previously mentioned, substantial expenditure may be required, so investment decisions should not be made before a cost-benefit analysis is undertaken. Although the fuel reduction treatment was the least effective mitigation treatment for reducing the risk of forest fire, the study did not specify where the treatment was applied and previous studies have found that fuel reduced areas close to houses are more effective at reducing house losses than landscape treatments (Stockmann et al. 2010; Bradstock et al. 2012; Gibbons et al. 2012; Penman et al. 2014a).

6.5 Future research

Findings from this thesis identify several directions for future research on prevention treatments to mitigate wildfire risk. Firstly, the starting point for assessing wildfire risk was an assessment of wildfire causes (Chapter 2). This was undertaken using fire incident data sourced from fire management agencies. The quality of the data is highly variable with inconsistencies both within and between agencies. In some cases, the data does not have the level of detail to meet research requirements. For example, the fire cause was unknown or unreported for 31% of wildfires. The fire incident data for the study on probability of containment of wildfires (Collins et al. 2018) had coarse resource data and could be improved by tracking arrival and departure times by resource type and the suppression tasks they undertook. Data quality and consistency issues have also been highlighted by other researchers (e.g. Maranghides et al. 2014; Hollis et al. 2015; Filkov
et al. 2018) and underlines the need for consistent data collection standards to enable the development of better models and tools to support fire management decision making. Comprehensive and accurate data is required to underpin models for analysing wildfire risk and investigate the effectiveness of wildfire prevention treatments.

The Bayesian Network model developed in this thesis could potentially be linked with a geographic information system to derive spatially explicit surfaces of wildfire house loss risk. This would require determining a suitable spatial resolution to conduct the analysis e.g. 1 km² and creating a grid of cells at that specified resolution in the geographic information system. Then for each of the input variables in the Network (i.e. those variables with links from the Bioregion node Fig 5.4) determining the probability distribution for each of the states of the variable within each grid cell. For the input variables that were derived from spatial data i.e. distance to road, house density, rainfall, vegetation type, fuel load and slope, these are relatively simple tasks. However, for other input variables, adjustments would need to be made to be able to create a spatially explicit Network. It is possible to obtain gridded reanalysis weather data for NSW, so the distribution of FFDI can be determined within each grid cell. For response time, it could be possible to derive response times based on distance to brigade stations and estimated travel speed (Duff et al. 2015). For aircraft and the number of tankers per ha of fire, conditional probability tables within each grid cell would need to be derived from expert elicitation or further studies. There are many advantages of developing a spatially explicit Network model. These include: creating maps of wildfire risk that can be used to identify areas of highest risk and inform treatment priorities; treatments can be targeted to specific areas to determine their effectiveness; what if scenarios can be run to identify the best placement for treatments; maps can be used to inform the public of their likely risk and encourage them to prepare their property.

The Bayesian Network framework is currently set to a bioregional scale, but it is possible to adjust the scale to a smaller scale such as subregion, NSW Rural Fire Service district or local government area. The smallest possible scale for the current configuration of the Network is NSW Rural Fire Service brigade, so it is possible to compare the relative risk between brigades which could be useful for determining resource allocations and treatment priorities.
Future research studies to include an economic evaluation of each prevention and suppression strategy in the Bayesian Network would be useful to inform investment decisions by fire managers. This would require quantification of both the direct (e.g. resources, equipment) and indirect costs (e.g. planning, administration/management) of each strategy (e.g. for prescribed burning Penman et al. 2014a) and the benefits associated with the reduction in house losses. There are many different approaches to economic evaluations (e.g. Milne et al. 2014; Thompson et al. 2017) and previous research has found a strong interest by fire managers in making greater use of economic evaluations in decision making (Calkin et al. 2013; Clayton et al. 2014).

Finally, the Bayesian Network model could be expanded to include mitigation strategies around houses and extended to consider the wildfire risk to other assets. The probability of a house being destroyed by a wildfire is determined by the level of fire exposure (radiant heat, flame contact and ember density) (Wilson and Ferguson 1986; Cohen 2000), the vulnerability (construction, design, material and siting) of the house (Wilson and Ferguson 1986; Cohen 2000; Mell et al. 2010) and suppression actions of fire agencies or residents (Wilson and Ferguson 1986; Ramsay et al. 1996; Whittaker et al. 2013). Penman et al. (2015) developed a Bayesian Network to quantify the relative influence on management strategies on the probability of house loss when a fire reaches a development however this would need to be modified to suit the Network model in this thesis or combined in a spatial context with one model to predict fire arrival at the development and another on a house to house basis. Potential variables to include in the Network are:

- house construction standard i.e. was the house built to planning and building construction standards for wildfire-prone areas?
- distance to vegetation i.e. what is the setback distance between the house and vegetation?
- suppression access i.e. is there defensible space?
- building density i.e. is there an opportunity for house-to-house-ignition?
- preparedness i.e. how well is the house and landscape immediately surrounding the house maintained?

Potential prevention and suppression treatments to include in the Network are:
- community education strategies i.e. a range of strategies that may influence preparedness;
- property suppression strategies i.e. a range of suppression strategies that may influence whether a house is destroyed;
- building resilience strategies i.e. a range of retrofit strategies to reduce the level of fire exposure.

The current model looks only at the wildfire risk to houses but there are many other social, economic and environmental assets valued by communities (Gill et al. 2013). These include human life, Aboriginal and non-indigenous heritage, agricultural, commercial/industrial complexes, energy infrastructure, tourist and recreation, commercial forests, drinking water catchments, endangered and vulnerable species and locally important species (Calkin et al. 2011; Ager et al. 2013; Gill et al. 2013). For each of these asset types, it would be necessary to determine how wildfire impacts the asset and the consequences (Fig 1.1). For assets where there is insufficient data available to fill the conditional probability tables, then expert elicitation can be used to populate the tables. Economic evaluations are likely to require using both market and non-market valuation techniques to estimate costs and benefits of fire management strategies. Bayesian Networks are a robust framework to undertake comprehensive wildfire risks assessments and provide opportunities for fire managers to explore mitigation strategies.
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Figure A1  Major agro-climatic zones in the study area in relation to subregions (source: Hutchinson et al. 2005).
**Table B1** Redacted long term data set of wildfires that destroyed houses (excludes fire name, locality and fire start date).

<table>
<thead>
<tr>
<th>Local government area</th>
<th>Ignition cause</th>
<th>Number of houses destroyed</th>
<th>Fire size</th>
<th>Number of days from ignition until first house destroyed</th>
<th>Fuel Type</th>
<th>Source ref. no.</th>
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<td>Fire size</td>
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Table B2 Sources of information for wildfires that destroyed houses.

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<th>Ref. No.</th>
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<td>1</td>
<td>Barber, EHE (1977) Report of the Board of Inquiry into the Occurrence of Bush and Grass fires in Victoria. Victorian Legislative Assembly. (Government Printer: Melbourne)</td>
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<td>2</td>
<td>Benalla Rural City Council Municipal Fire Management Plan Review December 2013</td>
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<td>Condon RW (1975) Report on bushfires in the Western Division of New South Wales, November 1974 to March 1975</td>
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<td>12</td>
<td>Country Fire Authority Annual Report 2007</td>
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<td>14</td>
<td>Country Fire Authority news 3/2/2012, Major Wodonga fire: 60 years on, <a href="http://54.206.64.143/news-major-wodonga-fire-60-years-on.html">http://54.206.64.143/news-major-wodonga-fire-60-years-on.html</a></td>
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<td>16</td>
<td>Department of Environment and Primary Industries ignitions database</td>
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<td>Duggin JA (1976) Bushfire history of the south coast study area, CSIRO Division of Land Use Research, Technical memorandum 76/13</td>
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<td>22</td>
<td>Forests Commission Victoria Annual Report 1982-83</td>
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<td>23</td>
<td>Hiatt J (1992) Inquest into the death of Shirley Anne Dudley, Inquest into the death of Emma Selina Tracy Burns, Fire Inquiry concerning fire at 13 Orana Road Kenthurst, Coroner’s Court Westmead, New South Wales</td>
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<td>24</td>
<td>Hiatt J (1994) New South Wales Bushfire Inquiry, Coroner’s Court Westmead, New South Wales</td>
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<td>31</td>
<td>Maynes KJ and Garvey MF (1985) Report on selected major fires in country areas of Victoria on 14 January 1985, Country Fire Authority, Victoria</td>
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<td>33</td>
<td>Milovanovich C (2004) Inquest into the death of Ronald Gillett and associated fire, Coroner’s Court, East Maitland, New South Wales</td>
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<td>36</td>
<td>Murrindindi Shire and Lake Mountain Municipal Fire Management Plan 2012, Version 5.2</td>
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<td>46</td>
<td>NSW Department of Bush Fire Services Annual Report 1989/1990</td>
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<td>NSW Office of Environment and Heritage fire history mapping database</td>
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<td>56</td>
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<td>71</td>
<td>Pyrenees Shire Municipal Fire Management Plan 2012-2015</td>
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<td>Richmond Valley Council (2002) 2002 Supplementary state of the environment report, Richmond Valley Council, Casino, NSW</td>
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<td>Smith S (2002) Bushfires, NSW Parliamentary Library Briefing Paper No 5/02</td>
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<td>Wilmoth W (1992) Record of investigation into a fire at Warrandyte on 25th February 1991, Case No. 626/91 State Coroner Victoria, Melbourne</td>
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<td>Woodend Water v Hyan 1990 (Victoria Supreme Court Full Court)</td>
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APPENDIX C SUPPLEMENTARY MATERIAL FOR CHAPTER 4
Table C1 Summary statistics for variables

Tpa = number of tankers per square root of final fire area, FFpa = number of firefighters per square root of the final fire area, EMM = earth-moving machinery, FFDI = forest fire danger index, GFDI = grassland fire danger index.

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<th>Variable</th>
<th>Fuel type</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
<th>Mean</th>
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### Table C2 Fire statistics by ignition cause

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Figure C1  Partial dependence plot for variables in the random forest model for containing forest fires within 2 to 4 hours of ground crews arriving at the fire. Variables are ranked in order of importance. Tpa = number of tankers per square root of final fire area, FFpa = the number of firefighters per square root of final fire area, EMM = earth-moving machinery, RH = relative humidity, FFDI = forest fire danger index, Acc = accidental, Del = deliberate, Lgt = lightning, Pow = powerline, Und = undetermined.
Figure C2 Partial dependence plot for variables in the random forest model for containing forest fires within 4 to 12 hours of ground crews arriving at the fire. Variables are ranked in order of importance. Tpa = number of tankers per square root of final fire area, FFpa = the number of firefighters per square root of final fire area, RH = relative humidity, EMM = earth-moving machinery, FFDI = forest fire danger index.
Figure C3  Partial dependence plot for variables in the random forest model for containing forest fires within 12 to 24 hours of ground crews arriving at the fire. Variables are ranked in order of importance. FFpa = the number of firefighters per square root of final fire area, Tpa = number of tankers per square root of final fire area, EMM = earth-moving machinery, FFDI = forest fire danger index, RH = relative humidity, Acc = accidental, Del = deliberate, Lgt = lightning, Pow = powerline, Und = undetermined.
Figure C4  Partial dependence plot for variables in the random forest model for containing grass fires within 2 to 4 hours of ground crews arriving at the fire. Variables are ranked in order of importance. EMM = earth-moving machinery, Tpa = number of tankers per square root of final fire area, RH = relative humidity, GFDI = forest fire danger index, FFpa = the number of firefighters per square root of final fire area, Acc = accidental, Del = deliberate, Lgt = lightning, Pow = powerline, Und = undetermined.
APPENDIX D SUPPLEMENTARY MATERIAL FOR CHAPTER 5
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<th>States</th>
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<td>Specific bioregion</td>
<td></td>
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<td>Rainfall</td>
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<td>0 – 450 mm; 450 - 550 mm; 550 – 650 mm; 650 - 800 mm; 800 – 1000mm; 1000-1200mm; &gt; 1200 mm</td>
<td>Regression tree of Clarke et.al. (in review) data and distribution of rainfall data</td>
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<td>Distance to road</td>
<td>The shortest distance to the nearest mapped road or fire trail.</td>
<td>0 – 40 m; 40 – 80 m; 80 – 200 m; 200 – 500 m; &gt; 500 m</td>
<td>Regression tree of Clarke et.al. (in review) data</td>
</tr>
<tr>
<td>House density</td>
<td>The number of houses within a 2 km radius</td>
<td>0 – 2 houses/2km; 2 – 4 houses/2km; 4 – 32 houses/2km; &gt; 32 houses/2km</td>
<td>Regression tree of Clarke et.al. (in review) data</td>
</tr>
<tr>
<td>FFDI (Forest fire danger index)</td>
<td>The mean annual proportion of days within each FFDI category</td>
<td>0 – 11 Low-Moderate; 12 – 24 High; 25 – 49 Very High; 50 – 74 Severe; 75 – 99 Extreme; &gt;= 100 Catastrophic</td>
<td>Existing fire danger index categorisation</td>
</tr>
<tr>
<td>Arson</td>
<td>Likelihood of arson ignition</td>
<td>0 – 0.05; 0.05 – 0.30; 0.30 – 0.80; &gt;0.80</td>
<td>Adapted from Pollack (2003)</td>
</tr>
<tr>
<td>Lightning</td>
<td>Likelihood of lightning ignition</td>
<td>0 – 0.05; 0.05 – 0.30; 0.30 – 0.80; &gt;0.80</td>
<td>Adapted from Pollack (2003)</td>
</tr>
<tr>
<td>Powerline</td>
<td>Likelihood of powerline-caused ignition</td>
<td>0 – 0.05; 0.05 – 0.30; 0.30 – 0.80; &gt;0.80</td>
<td>Adapted from Pollack (2003)</td>
</tr>
<tr>
<td>Other</td>
<td>Likelihood of an ignition from other accidental human-caused ignition</td>
<td>0 – 0.05; 0.05 – 0.30; 0.30 – 0.80; &gt;0.80</td>
<td>Adapted from Pollack (2003)</td>
</tr>
<tr>
<td>Response time</td>
<td>Time between when the fire was reported and ground crews arriving at the fire.</td>
<td>0 – 15 min; 15 – 25 min; 25 – 35 min; &gt; 35 min</td>
<td>Distribution of response times in Collins et al. (2018)</td>
</tr>
</tbody>
</table>

---

1 Clarke, H, Gibson, R, Cirulis, B, Bradstock, RA, Penman, TD (in review) Developing and testing models of the drivers of ignition in southeastern Australia. *Journal of Environmental Management*

<table>
<thead>
<tr>
<th>Node</th>
<th>Description</th>
<th>States</th>
<th>Discretisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tankers</td>
<td>The peak number of appliances at the fire divided by the square root of the final fire area.</td>
<td>$0 - 1; 1 - 2; 2 - 3; &gt; 3$</td>
<td>Distribution of tankers per ha of fire in Collins et al. (2018)</td>
</tr>
<tr>
<td>Fuel load</td>
<td>The estimated fuel load (t/ha)</td>
<td>None; $0 - 5$ t/ha; $5 - 12$ t/ha; $12 - 20$ t/ha; $20 - 30$ t/ha; $&gt; 30$ t/ha</td>
<td>Hines et al. (2010)$^3$</td>
</tr>
<tr>
<td>Slope</td>
<td>The % of bioregion within each slope class</td>
<td>$0 - 5^o; 5 - 15^o; 15 - 30^o; &gt; 30^o$</td>
<td>Common categorisation of slope</td>
</tr>
<tr>
<td>Aircraft</td>
<td>Was aircraft used to control the fire?</td>
<td>Yes; No</td>
<td></td>
</tr>
<tr>
<td>Vegetation type</td>
<td>The % of bioregion within each type</td>
<td>Forest; grassland; nonfuel</td>
<td>Broad types</td>
</tr>
<tr>
<td>Arson contained</td>
<td>Likelihood of an arson ignition contained</td>
<td>Very High &lt;$0.05$ uncontained; High $0.05 - 0.25$ uncontained; Mid $0.25-0.50$ uncontained; Low $&gt;0.50$ uncontained</td>
<td>Adapted from Pollack (2003)</td>
</tr>
<tr>
<td>Lightning contained</td>
<td>Likelihood of a lightning ignition contained</td>
<td>Very High &lt;$0.05$ uncontained; High $0.05 - 0.25$ uncontained; Mid $0.25-0.50$ uncontained; Low $&gt;0.50$ uncontained</td>
<td>Adapted from Pollack (2003)</td>
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<tr>
<td>Powerline contained</td>
<td>Likelihood of a powerline ignition contained</td>
<td>Very High &lt;$0.05$ uncontained; High $0.05 - 0.25$ uncontained; Mid $0.25-0.50$ uncontained; Low $&gt;0.50$ uncontained</td>
<td>Adapted from Pollack (2003)</td>
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<tr>
<td>Other contained</td>
<td>Likelihood of an ignition from other accidental human-caused ignition contained</td>
<td>Very High &lt;$0.05$ uncontained; High $0.05 - 0.25$ uncontained; Mid $0.25-0.50$ uncontained; Low $&gt;0.50$ uncontained</td>
<td>Adapted from Pollack (2003)</td>
</tr>
<tr>
<td>Arson house loss</td>
<td>Likelihood of a house destroyed by an arson ignition.</td>
<td>None $&lt;$ 0.0001; Low 0.0001 – 0.02; Mid 0.02-0.2; High $&gt;0.2$</td>
<td>Adapted from Pollack (2003)</td>
</tr>
<tr>
<td>Lightning house loss</td>
<td>Likelihood of a house destroyed by a lightning ignition.</td>
<td>None $&lt;$ 0.0001; Low 0.0001 – 0.02; Mid 0.02-0.2; High $&gt;0.2$</td>
<td>Adapted from Pollack (2003)</td>
</tr>
</tbody>
</table>

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<th>Description</th>
<th>States</th>
<th>Discretisation</th>
</tr>
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<tr>
<td>Powerline house loss</td>
<td>Likelihood of a house destroyed by a powerline ignition</td>
<td>None &lt; 0.0001; Low 0.0001 – 0.02; Mid 0.02-0.2; High &gt;0.2</td>
<td>Adapted from Pollack (2003)</td>
</tr>
<tr>
<td>Other house loss</td>
<td>Likelihood of a house destroyed by an ignition from other accidental human-caused ignition</td>
<td>None &lt; 0.0001; Low 0.0001 – 0.02; Mid 0.02-0.2; High &gt;0.2</td>
<td>Adapted from Pollack (2003)</td>
</tr>
<tr>
<td>All house loss</td>
<td>Likelihood of a house loss occurring.</td>
<td>0 - 1</td>
<td></td>
</tr>
<tr>
<td>Ignition management</td>
<td>Decision node representing the chosen level of ignition management effort to reduce arson or powerline ignitions</td>
<td>Current programme; 10% arson ignitions reduced; 20% arson ignitions reduced; 10% powerline ignitions reduced; 20% powerline ignitions reduced</td>
<td>Management level of interest</td>
</tr>
<tr>
<td>Fuel management</td>
<td>Decision node representing the chosen level of fuel management effort for the area</td>
<td>No fuel treatment; Current practice; 1% increase in prescribed burn effort; 2% increase in prescribed burn effort; 5% increase in prescribed burn effort</td>
<td>Management level of interest</td>
</tr>
<tr>
<td>Suppression</td>
<td>Decision node representing the chosen level of suppression effort for the area</td>
<td>Current resources, 20% more tankers per ha of fire available; 20% less tankers per ha of fire available; response time increases by 20%; response time decreases by 20%</td>
<td>Management level of interest</td>
</tr>
</tbody>
</table>
Table D2 The number of grass and forest fire incidents include in the study by bioregion and the mean % forest area treated by prescribed burning annually.

<table>
<thead>
<tr>
<th>Bioregion</th>
<th>Bioregion code</th>
<th>No. of grass fire incidents</th>
<th>No. of forest fire incidents</th>
<th>Mean % forest area treated by prescribed burning annually</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brigalow Belt South</td>
<td>BBS</td>
<td>542</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobar Peneplains</td>
<td>CP</td>
<td>129</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Darling Riverine Plains</td>
<td>DRP</td>
<td>336</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nandewar</td>
<td>NAN</td>
<td>139</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New England Tablelands</td>
<td>NET</td>
<td>135</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NSW North Coast</td>
<td>NNC</td>
<td>358</td>
<td>414</td>
<td>0.88</td>
</tr>
<tr>
<td>Riverina</td>
<td>RIV</td>
<td>331</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sydney Basin</td>
<td>SB</td>
<td>996</td>
<td>840</td>
<td>1.84</td>
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<tr>
<td>South Eastern Highlands</td>
<td>SEH</td>
<td>279</td>
<td>143</td>
<td>1.01</td>
</tr>
<tr>
<td>South Eastern Queensland</td>
<td>SEQ</td>
<td>250</td>
<td>196</td>
<td>0.30</td>
</tr>
<tr>
<td>NSW South Western Slopes</td>
<td>NSS</td>
<td>985</td>
<td>232</td>
<td>0.37</td>
</tr>
</tbody>
</table>