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NATURAL DISASTER RESILIENCE GRANTS SCHEME – VICTORIA

Indicators of Fire Vulnerability:

Risk Factors in Victorian Settlements

DRAFT FOR REVIEW

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1 Introduction and Statement of Aims

Recent research shows that as metropolitan and major regional area areas grow quickly in Australia, proportionally greater amounts of land are being developed as fragmented, low density peri-urban settlements (Low Choy, Sutherland, Gleeson, & Sipe, 2008). This development form will expose increasing numbers of houses to bushfire threats (Buxton, Haynes, Mercer, & Butt, 2011). Ensuring that new settlements can deal with bushfire threats is a central element of ensuring Australian settlements' long-term resilience, particularly as the incidence and intensity of extreme weather increases (Lucas, Hennessy, Mills, & Bathols, 2007).

Understanding which patterns of settlements better withstand bushfire attack allows development of an index of inter-related factors that can be used as an assessment tool for existing and proposed human settlements in bushfire prone areas. Further, comparison of the index to extant policy and will allow for critique and improvement of existing planning regulations, spatial policy and design guides. Current design guides tend to focus on individual buildings, giving little comprehensive attention to the arrangements of settlements overall (Hughes & Mercer, 2009), a form of mal-adaptation which encourages increased amounts of settlement in areas of high bushfire incidence.

The relevant features of urban morphology include, but are not restricted to: the density per hectare of buildings, the size and shape of groups of buildings, the type and amount of vegetation in gardens and public areas, the distance between structures, the distance to, amount of and type of flammable vegetation, the width and layout of roads and reserves, the climate zone, and the materials used in structures. Importantly, current regulation-based urban planning approaches consistently demonstrate serious shortcomings in predicting and responding to bushfire risks (Buxton, Haynes, Mercer, & Butt, 2010).

This project sets out to study readily observable urban design parameters and their implications for predicting house loss in unplanned bushfires. The study will focus on a single detailed case study with the broader objective of working towards a predictive house loss index based on urban design and fire behaviour parameters.

This objective is driven by the need to communicate urban design principles in a simple and effective way to practitioners that are not necessarily well versed in bushfire related urban design, and to demonstrate a repeatable method of urban design assessment.

2 Literature and Policy Review

2.1 Fire and settlement patterns

This section of the report reviews literature and policy documents with a focus on the findings of the relationship between fire risk and settlement patterns. Specifically, it discusses the meaning of the 'wildland-urban interface' in the context of bushfire, empirical studies of fire at the interface with a focus on settlement patterns.

2.1.1 THE WILDLAND-URBAN INTERFACE

In their text *The Environment as Hazard*, Burton et al argue that environmental processes, such as fire, only become hazards when they interact with the 'human use system' (1993, p. 32). The focus of this research is the fire interaction with the 'use system', particularly settlements at the wildland-urban interface (WUI).

In defining the WUI, it must be noted that there are many other terms that refer to the areas where urban areas meet and interact with vegetation in the context of bushfire hazard. The wildland–urban interface is defined as being an area where homes and human infrastructure meet or intermingle with wildland vegetation (Radeloff et al., 2005; Theobald and Romme, 2007). Gill and Stepenhs (2009) also describe this area as when structures are built next to relatively unmodified forests, shrublands or grasslands (wildland/bush) or next to rural properties where vegetation is largely modified.

Globally, the increase in populations has most often resulted in the expansion of settlements close or within wildland vegetation. The increase of the density of populations living in WUIs is identified as increasing overall bushfire risk by (Cottrell & King, 2007, p. 25). This was also the findings of Theobal and Romme (2007). While urban developments close to or within wildland vegetation are often associated with environmental and socio economic concerns, they are mainly considered in the context of fire prevention and suppression (e.g. Avalapati et al. 2005, Radeloff et al. 2005, Stephens 2005)

The WUI is often classified and characterised for many studies and applications. The objective of characterising the WUI is to assess the risks associated with these interfaces and provide appropriate prevention measures, or reduce a type of interface that might present more risk. Characterisation and classification often distinguish between those types of WUI that are more within wildland from those that are surrounded by wildland or are adjacent to wildland. Also taken into consideration is the extent and fuel characteristics of the wildland, the density and configuration of dwellings and accessibility (street networks), and the density of the population. The consideration of certain characteristics for a variety of elements varies nationally (Balcolmbe, 2007, pp. 194-196; Cottrell, 2005) and internationally. Some international examples being where Gorte (2006, p. 7) and Cova (2005, p. 100) categorise the WUI in the United States and Lampin et al (2010 and 2011) in characterising and mapping WUI in Europe.

Beyond the classification of interface types, there is some discussion in the literature of the built form of WUI settlements. On settlement morphology, the Australian literature identifies 'modular' or homogenous subdivisions with long interface edges, along with narrow streets and poor access and exit points, as particularly risky (Cottrell & King, 2007, p. 25; Lowe, Haynes, & Byrne, 2008, p. 22). In the United States, the importance of street networks is also recognised, with Cova (2005, p. 100) nominating settlements 'with a static road network and steadily increasing housing stock' as fire-prone. The relationships between settlement morphology and vegetation are also emphasised. In Australia, this includes urban riverine, ridge-top forest and urban bushland, which all 'contribute to the richness of urban design for sustainability and desirable settlements', while increasing bushfire risk (Cottrell & King, 2007, p. 25). Potential bushfire hazard risk is related to topography and aesthetics, with the aesthetic values of views and vegetation leading to the location of dwellings on hill-slopes and ridges, where they are especially vulnerable to bushfire (Little, 2003, p. 30). Biodiversity conservation laws are also noted as driving retention of native vegetation, in direct conflict with requirements for buffers and setbacks at the WUI (Cottrell, 2005, p. 25; Little, 2003, p. 30). Finally, density, or the number of buildings or people living in WUI settlements by geographical size, is identified as increasing overall bushfire risk, 'by putting more people and infrastructure into a hazard zone' (Cottrell & King, 2007, p. 25).

In addition to general descriptions of the characteristics of WUI settlements, particular locations have been nominated as especially risk-prone. In Australia, Collins argues that the most at-risk urban interface developments are found 'in bush-surrounded, isolated streets' in the outer suburbs of Sydney, Melbourne, Hobart and Adelaide (2009, p. 372). The nature of street networks highlighted as exposure to most risk are single streets along a ridge-line with bush on either side in the northern suburbs and Blue Mountains of Sydney and the Dandenong ranges in Melbourne, which have a one escape route, and isolated roads lacking connectivity in the Adelaide Hills. The design of Canberra has also been marked as risk-prone, being intentionally designed as a garden city surrounded with vegetation (Cottrell & King, 2007, p. 25).

Although Cottrell and King note that there are 'high levels of diversity between and within locations' (2007, p. 23) with respect to WUI, some clear themes exist around the risk factors associated with particular built form morphologies. Stephens and Collins (2007) consider that some efforts have been made in the USA to reduce house ignitions by taking into account building design, material defensible space, but that much work still needs to be done to address the external threat to structure from a land planning perspective.

2.1.2 BUSHFIRES AT THE INTERFACE

Bushfire incidents at the WUI in Australia have been well documented and studied in academic research and commissions of enquiry (see Ellis, Kanowski, & Whelan, 2004; Geosciences Australia, 2003; Leonard, 2009; Teague, McLeod, & Pascoe, 2009). Of the 11,092 dwellings lost in Australia over the last 100 years, Blanchi et al (2010) found that the majority of losses can be attributed to six iconic bushfire events. Further, that of the three bushfires where more than 1,000 houses were lost, the 2009 Black Saturday bushfire counted the most destroyed dwellings; Hobart 1967 and Ash Wednesday 1983 being the other two significant events. Although the 2009 Black Saturday fire occurred over a widespread area and is the result of multiple ignition points, the fires are treated as one event. The merging of the separate incidents into one bushfire was seen as sensible given that the same large-scale weather process supported the fires on the day. Table 1 below details the houses lost in the 2009 Black Saturday event in Victoria by region.

Table 1. Houses destroyed in the 2009 Black Saturday bushfire in Victoria (Source: Victorian Bushfires Royal Commission, (2009). Exhibit 980

Region	Number of dwellings destroyed
Bendigo	58
Beechworth	38
Bunyip	31
Churchill	145
Coleraine	1
Delburn	44
Hepburn	2
Horsham	13
Kilmore-East	1242
Murrindindi	538
Narre Warren	7
Redesdale	14
Total	**2133**

The choice of scale for the studies and commissions of enquiry have determined which aspects of human settlement may be explored. For instance, those that are undertaken at a landscape scale allow for exploration of town planning, while those at house level tend to focus more on house design and construction in the context of the bushfire event(s).

There are many examples of landscape scale modelling (e.g. Ahern & Chladil, 1999; Bar Massada, Radeloff, Stewart, & Hawbaker, 2009; Bradstock & Gill, 2001; Lampin-Maillet, Long-Fournel, Ganteaume, Jappiot, & Ferrier, 2011,Gibbons, 2012; Menakis, Cohen, & Bradshaw, 2003; Salas & Chuvieco, 1994; Theobald & Romme, 2007) and these include different variables such as vegetation (e.g. type, fuel load, structure, moisture content), output from fire behaviour models (and fire simulation), topography, climate, fire regime, fire history, socio-economics, human activities, land use and land cover. The objective of the assessments at landscape scale can vary greatly ranging from informing land use management, forest management and fire management. Of the landscape scale analysis published, we will discuss some of the most relevant publications in more details.

At a landscape scale Theobald and Romme (2007) explore the categorisation and mapping of WUI, taking into consideration expected growth and potential bushfire hazard. The authors note that 'expansion of low-density residential development at the wildland–urban interface has been widely recognized as a primary factor influencing the management of US national forests'. As such, an understanding of patterns and trends of residential forest expansion inform hazard management and mitigation.

In addressing the need for characterisation of risk and discrimination of types of WUI in southern France Lampin-Maillet and Long-Fournel, et al. (2011) also discuss changes in urbanisation. They found that an increase in urbanisation and the transition of traditionally agricultural land to unmanaged shrubland and forests increased bushfire hazard. The study focuses on improving our knowledge of relationships between WUI environments and fire risk to increase the efficiency of wildfire prevention. Considering the spatial organization of settlements and the structure of fuel vegetation, they suggest that different categories of WUI require different prevention actions and communication campaigns.

In the analysis of dwelling vulnerability in Colorado in the United States by Bhandary and Muller (2009) many factors pertaining to the settlement morphology were assessed. Using logistic regression, they found that eight of the variables were statistically significant in predicting house vulnerability. These were vegetation density, area of defensible space, adjacency of parcel to public land, road width, subdivision morphology, proximity of a house to a fire station, assessed value, and parcel slope . The authors concluded that the model results supported current land use planning strategies for risk mitigation, such as vegetation reduction, topographical considerations in site selection, and improved access to fire stations.

Harris and Anderson et al (2012) reviewed observations from 79 wildfires (1939 to 2009), the majority occurring in Victoria, for the purposes of developing a bushfire severity scale based on community impact (financial loss in the form of loss of life and property). The authors concluded that the power of the fire was the most significant descriptor for predicting house loss and fatalities and included considering simple planning metrics such as house density.

A large scale assessment of house loss in southern California from bushfires (5500 structures that were destroyed or damaged by wildfire since 2001) was conducted by Syphard, A. D., J. E. Keeley, et al. (2012) in an effort to determine if housing location and arrangement affected the likelihood that a home will be lost. Variables included observations and metrics defining housing arrangement, house location, biophysical properties (fuel loads, slope, etc.) and firefighter access. This study found empirically based maps developed using housing pattern and location performed better in distinguishing hazardous from non-hazardous areas than maps based on fuel distribution. This finding leads them to conclude that land use planning may be a critical tool for reducing fire risk.

Price and Bradstock (2013) assessed 3518 houses located within the area affected by four fires during the Black Saturday 2009 bushfire. Using the location of houses, the state vegetation classification, extents of crown fire and slope they determined the proportion of these at ever increasing concentric areas for each house. They found that 72% of house loss could be explained by the proportion of adjacent forest, the proportion of crown fire within that proportion of forests and proportion of neighbouring houses. Three deductions are asserted by these findings; that forests need to be managed to mitigate crown fire, this management may have to extend 1km from the house and that higher proportions of nearby houses increase risk of loss. However, given these assertions, the authors conceded that risk mitigation may be better applied through building regulations.

Several other Australian studies have looked specifically at the relationship between distance to unmanaged vegetation (wildland) and a building's risk in fire events. Ahern and Chladil (1999) used data from the 1967 'Black Tuesday' fires in Hobart, the 1983 'Ash Wednesday' fires in the Otway region of Victoria and the 1994 Como-Jannali fires in NSW. They found that 95 percent of all buildings destroyed in bushfires were within 100 metres of vegetation. In a 2004 study using data from the 2003 Canberra bushfires, the 1994 Sydney bushfires, and the 1983 'Ash Wednesday' Victorian and South Australian bushfires, Chen and McAneney found that 'although distance to bushland is not the only variable determining bushfire vulnerability, it is demonstrably the most important' (Crompton, McAneney, & Chen, 2010, p. 309). Across data from the three fire events, they concluded that the maximum distance at which buildings were destroyed was typically less than 700 m from vegetation, and that the probability of destruction was a simple linear and decreasing function of that distance. The overall probability of dwellings located at the interface being destroyed was found to be around 60 percent, with patterns of destroyed dwellings displaying 'neighbourhood clustering' (Chen & McAneney, 2004, p. 1). A third study by Crompton et al. of the 2009 Victorian 'Black Saturday' fires in Kinglake and Marysville found that 25 percent of destroyed buildings were located within bushland and 60 percent were within 10 m of vegetation (2010, p. 309). Newnham and Siggins et al (2012) explored the relationship between distance to vegetation and buildings through investigating the explicit definintion of wildland. Lidar data was used to derive both horizontal and vertical profiles of vegetation in order to specifically identify unmanaged vegetation (wildland). In comparing their analysis to similar studies they found an improvement in explaining house loss considering distance to wildland. The authors concede that while this is an improvement, the classification of wildland is dependent on parameters used in the lidar processing.

The relationship between urban vegetation and bushfire risk has been discussed in the literature with particular reference to the 2003 Canberra bushfires. In their report from the *National Inquiry on Bushfire Mitigation and Management*, Ellis et al. (2004) noted that the Canberra fire demonstrated the risk from urban vegetation. Specifically noting the penetration of fire into suburbs beyond the WUI attributed to the 'continuity of fuel loads in gardens and extensive areas of open space between and within suburbs' (p.28). The analysis by Leonard (2009) found that ember attack was the main cause of loss in the 2003 Canberra bushfire. Further, this fine fuel was available because of the abundant vegetation and the effects of a long drought.

Along with vegetation, the morphology of road networks has received some attention in the Australian literature. Leonard (2009) analysed the 1994 Sydney region fires in which he found that there was clear evidence of the value of perimeter roads around subdivisions in reducing risk to buildings. Fire trails behind buildings which faced central roads were also found to be beneficial, albeit to a lesser extent . A subsequent study by Callaghan et al. of the 2003 Canberra fires concluded that perimeter (or 'edge' roads) offered a similar level of protection to fire trails, with fire trails being a more cost effective option (2010, p. 58).

An example of house level analysis can be found in Siggins et al. (2013) analysis using 3-dimensional modelling of radiant heat flux (heat energy) incident on a house. This was a study of the 2009 Kinglake West bushfire and involved generating a 3-dimensional scene of event. The scene included parabolic fire simulation, house and landscape features, weather parameters and house design parameters. House vulnerability was effectively assessed using this method. Assessments such as this are key in informing building standards directed towards mitigating loss from bushfire events.

Platt (2006) describes a model for identifying the probability of land being developed for exurban, interface development in the US. In simulating exurban development, the model included distance to public lands, distance to streams, slope, distance to employment, neighbourhood exurban density, and zoning (p.752). For example, slope was negatively related to probability of future growth as steep slopes are difficult to build up on (p.754). This approach includes similar variables to those which will identify areas of fire risk.

2.1.3 SOCIO-DEMOGRAPHIC FACTORS

While not a factor that is directly dealt with in this study, it is important to note that Blanchi and Leonard (2008) found that human influence, in the form of a number of factors, plays a major role in house loss. Some of the factors relevant to loss in a bushfire event are related to the presence of an able person before during and after the fire event. Whittaker et al. (2012, p. 1) note that bushfire research in Australia has focused on physical characteristics of fire hazard, with 'relatively little consideration of how cultural, economic, political and social factors shape vulnerability'.

The relationship between socio-demographic factors and bushfire risk is now an emergent theme in literature and policy. Writing on wildfire risk in the US, Muller and Schulte (2011, p. 62) identify four 'channels of influence' through which demographic characteristics shape the fire risk of communities. These are the effect of rural or urban residence on attitudes toward the role of government, the effect of income and education on attitudes toward risk reduction, the effect of housing tenure and occupancy on risk mitigation, and effects of high population growth on perception of risk.

2.2 Settlement policy and bushfire

Policy responses to bushfire hazards in Australia include emergency management, building standards, and land use planning. Burton et al (1993) identify four societal stages of coping with hazards; loss adsorption, acceptance, reduction and change. Land use planning policy enacts the last two stages through reduction of the bushfire hazard (e.g. vegetation management), or land use or living methods, for example by prohibiting development in particular areas.

In terms of reducing bushfire hazard, land use planning can employ statutory controls, as summarised by Little (2003, p. 30) and outlined in Table 2. These land use planning controls can be complemented by building standards for design and materials that improve the chances of a building surviving bushfire event.

Table 2. Little's (2003) summary of statutory controls

Category	Example Implementation
Siting principles	Locating new development away from ridge tops and steep slopes
Set-backs	Separating houses from vegetation hazard
Access	The inclusion of edge roads that can act as setbacks and provide ingress and egress for emergency vehicles and evacuation
Design and staging development	Minimising the length of perimeters facing vegetation, avoiding long and complex road patterns, and extending development from the perimeters of existing settlements
Water supply	Providing for a ring main system along edge roads and static water supplies

The final societal stage outlined by Burton et al. (1993), change, could also be enacted through land use planning. However, as the review of current policy documents will demonstrate, this has not been the case in Australian planning policy to date. Schwab et al. set out the spectrum of planning policy responses to fire hazard, from 'land acquisition and relocation of the neighbourhood and community at one end' to the 'imposition of relatively minor construction changes at the other' (2005, p. 266). They note that after a major fire event, the desire to return to 'normality' often leads to reconstruction of development in the same risky conditions and locations. They argue that the following staged questions should be asked before reconstruction is permitted (Schwab, 2005):

1. Should the neighbourhood or community be rebuilt or relocated?
2. If it should be rebuilt in the same location, should it be replanned?
3. To what extent should new conditions be enforced to achieve greater safety as the area is rebuilt?
4. Should damaged buildings be subject to retrofitting requirements as they are repaired?

5. Should restrictions be made on new development on vacant land in similar areas?

The National Inquiry on Bushfire Mitigation and Management (2004, p. xiv) found that planning processes to 'ensure that built assets are not placed in areas of high fire risk' was a key risk mitigation measure. While actual planning responses in Australia have avoided the first question of whether the community should be relocated and move straight to addressing the subsequent considerations around risk-reduction in-situ. This may change in the future, in the context of broader shifts in planning policy in response to climate change and uncertainty. The use of 'planned retreat', where planning systems are used to gradually move development away from the direct impacts of climate change hazard such as sea level rise, is being adopted (DeSousa, 2010). A planned retreat approach could be applied to areas of bushfire vulnerability. This would be the fourth 'change' stage of coping with the hazard, and would require a major institutional and societal shift in the planning system and property rights.

2.2.1 CURRENT POLICY FOR BUSHFIRE

A summary of planning and building system controls relating to settlement level bushfire risk at federal, state and territory levels is outline in Table 3. All jurisdictions bar the Northern Territory use a combination of the building control system and the planning control system. The Northern Territory does not have any specific bushfire policy. Non-statutory guidelines for development in areas of bushfire risk are also common.

Table 3 Policy and Legislation for Bushfire and Settlements, Australia

Jurisdiction	Planning System Controls	Building System Controls	Non-Statutory Planning Guidelines
National		Building Code of Australia (BCA) Australian Standard (AS) 3959	
ACT	Territory Plan, refers to NSW 'Planning for Bushfire Protection'	Applies BCA and AS 3959	Planning for Bushfire Risk Mitigation in the ACT (2006) Strategic Bushfire Management Plan (2009)
NSW	Environmental Planning and Assessment Act 79BA (2013) Rural Fire Act (1997) Planning for Bushfire Protection (2006) Standards for Bush Fire Hazard Reduction Works in SEPP 14 - Coastal Wetlands(2010)	Building and Planning integrated; AS 3959 applies	
NT	N/A	N/A	N/A
QLD	State Planning Policy (2013)	Applies BCA and AS 3959	
SA	Planning Strategy (2007-2011)	Applies BCA and AS 3959	Building a Home in Bushfire Prone Area (2003)
TAS	Planning Note 11 Resource Planning and Development Commission, (1997) State and Local Fire Protection Plans	Applies BCA and AS 3959 (with local variation)	Guidelines for Development in Bushfire Prone Areas of Tasmania (2005)
WA	State Planning Policy 3.4 Natural Hazards and Disasters (2006)	Applies BCA and AS 3959	Building for better protection in bushfire areas (2011)
VIC	Victorian Planning Provisions 44.06 Bushfire Management Overlay (2013)	Applies BCA and AS 3959	

At the national level, the Building Code of Australia (BCA) and Australian Standard (AS) 3959 cover building and site design. The BCA comprises the first two volumes of the National Construction Code (Australian Building Codes Board, 2011). It is produced and revised annually by the Australian Building Codes Board on behalf of the federal and state and territory Governments. All states and territories use the BCA for building regulations. It contains technical provisions for the design and construction of buildings and other structures, including fire resistance. Part 3.7.4 of the second volume addresses construction in bushfire exposure areas. The BCA refers to the Australian Standard AS3959 for the determination of bushfire attack category for every state (except NSW which assesses the level of bushfire attack in their document: *Planning for Bushfire Prevention* 2006). Construction requirements are then set out, based on the bushfire attack category (medium, high or extreme). Requirements address building elements such as flooring systems, external walls and doors, windows, verandas and decks. These requirements are based on the building itself only, not site or subdivision level design.

At a state and territory level, building system controls work together with planning system controls and non-statutory guidelines to address bushfire exposure at a building and site level. The next part of this section will highlight only where these controls and policies directly address subdivision or settlement design.

Policy guidelines and planning controls define spatial areas of 'bushfire risk' in different ways. The NSW Rural Fire Service's (NSW RFS) guidelines *Planning for Bushfire Protection* (NSW Rural Fire Service, 2006) uses a 'high', 'medium' and 'low' bushfire hazard approach, with the potential severity of the fire hazard dictated by climatic conditions, vegetation (fuel quantity, distribution and moisture) and slope. In Victoria, a process to define 'bushfire prone' areas arose from the recommendations of the Victorian Bushfires Royal Commission (VBRC), and came into effect in September 2011 (Victorian Government, 2013. The process by which areas are designated 'bushfire prone' is based on Department of Environment and Primary Industries (DEPI) state-wide hazard mapping, although the criteria are not specified.

The ACT and Victoria address open space from a settlement design perspective. In the ACT's *Planning for Bushfire Risk Mitigation General Code* (2008) takes the approach of 'balancing' bushfire risk with Canberra's planning tradition of open space provision ., The balance being between the aesthetic and recreational values of open space, and risk. In the Victorian CFA's *Planning Guidelines for Subdivisions* (2010) open space is seen as a bushfire mitigation tool in settlement design. Specifically, citing natural and built open space features such as wetlands, golf courses and sports ovals as providing a barrier to slow or stop fire progression .

Road network design, egress and defence capacity are related elements in the Victorian Planning Provisions 44.06. The CFA sets out road access requirements, including that:

- all subdivisions must have at least two access options,
- roads within the subdivision should be linked to roads in neighbouring subdivisions, and
- perimeter (or 'edge') roads are encouraged while dead-end roads and cul de sacs are discouraged (2010, p. 8).

The ACT code focuses on road access requirements for emergency vehicles, such as an edge road or fire trail. They also specify water supply infrastructure capacity levels, including fire hydrants and provision for emergency vehicle hardstand (2008, p. 7). The NSW guidelines specify that roads in new subdivisions provide safe access, egress and defendable space for emergency services (NSW Rural Fire Service, 2006, p. 11). Setbacks and edge conditions are linked in terms of their treatment. The ACT has 'Urban Edge Management Zones' with a design standard for edge conditions between urban development and vegetation. This includes management fencing, an adequate fire break, and access tracks for land management and other maintenance authorities (Callaghan et al., 2010, p. 58). The settlement 'edge' is also managed through higher residential design and construction standards (minimum level 1 BCA) within the first 100m of a 'Home Asset Protection Zone' to lessen the risk of ember attack (ACT Planning and Land Authority, 2008, p. 7).

The NSW *Planning for Bush Fire Protection* (2006) policy sets out detailed statutory requirements for subdivision design in Australia. All development on land designated as 'bushfire prone' must satisfy the aim and objectives of the policy, using a performance based approach .The general principles of the policy include:

- minimum setback, or defendable space, from the hazard being always required,
- the smaller the interface a development has fronting the bush fire hazard, the lower the risk, and
- that bushfire protection measures should be located within the overall development and not on adjoining lands .

In addition to these general principles, the policy has specific objectives for site and subdivision design. For residential and rural residential subdivision, objectives include:

- minimising the perimeters of the subdivision exposed to the bush fire hazard, noting that hourglass shapes, which maximise perimeters and create bottlenecks, should be avoided;
- minimising bushland corridors that permit the passage of bushfire;
- providing for the siting of future dwellings away from ridge-tops and steep slopes, within saddles and narrow ridge crests;
- providing and siting open space and public recreation areas as accessible public refuge areas or buffers;
- ensuring the continuing maintenance of asset protection zones;
- provide clear and ready access from all properties to the public road system for residents and emergency services; and
- ensuring the provision of water and other services to facilitate effective firefighting defence (NSW Rural Fire Service, 2006, p. 17).

By setting out morphological considerations for reducing bushfire risk in subdivision design, these objectives provide some direction for the development of indices to asses both new subdivision proposals and existing subdivisions.

Replacing multiple policies, the State Planning Policy (SPP) (2013) was introduced to simplify and clarify planning and development requirements in QLD. The SPP covers land use planning and development and how they must be dealt with in planning schemes, council development assessment processes and in designating land for community infrastructure. Local governments are directed how to make and amend local planning instruments and assess development applications, and assists developers preparing development applications. The SPP also provides a public interactive mapping tool and guidance and support resources online. With respect to bushfire hazard, a development application for a material change of use in bushfire prone areas is assessed against the following requirements:

(1) avoids natural hazard areas or mitigates the risks of the natural hazard, and
(2) supports, and does not unduly burden, disaster management response or recovery capacity and capabilities, and
(3) directly, indirectly and cumulatively avoids an increase in the severity of the natural hazard and the potential for damage on the site or to other properties, and
(4) avoids risks to public safety and the environment from the location of hazardous materials and the release of these materials as a result of a natural hazard, and
(5) maintains or enhances natural processes and the protective function of landforms and vegetation that can mitigate risks associated with the natural hazard, and

Areas considered to be in a bushfire hazard area are those classified as being medium, high or very high potential bushfire hazard.

The Bushfire Management Overlay (BMO) is Victoria's main planning system control for bushfire risk and replaced the Wildfire Management Overlay in November 2011 (Victorian Government, 2011b, p. 1). An applicant for a planning consent on land within the BMO must provide a description of the site and land 250 metres from the site boundary. This may include features such as vegetation types, condition and coverage, existing road networks, any major landscape features and topography . This enforces the description of a site's context within a wider settlement morphology.

In response to the VRBC recommendations, the Victorian Government developed a Bushfire Integrated Planning and Building Framework. The aim being to 'strengthen the consideration of bushfire at different stages of the planning process and better integrate the planning and building systems' (Victorian Government, 2011a, p. 1). The principal changes introduced by the Framework are:

- a new emphasis on the priority of protecting human life in building and planning decision-making,
- the application of the precautionary principle to development in areas at most risk from bushfire.

The emphasis on protecting human life is a shift from the previous policy outlined in the Wildfire Management Overlay (WMO). This stated that new development should 'not significantly increase the threat to life and surrounding property from wildfire' (Victorian Government, 1997, emphasis added).

At a state-wide macro scale mapping of the bushfire hazard has been carried out for the Bushfire Management Overlay (BMO). The BMO came into force in November 2011 (last updated 2013) and replaced the WMO. Under the WMO, mapping of bushfire risk was based on areas of forest greater than five hectares in size and with a vegetation density of greater than 80 per cent. The BMO mapping is based on a more detailed set of criteria, including vegetation, weather characteristics and slope (see

The three categories of the BMO are:

1. Low bushfire threat area – there are no specific bushfire protection measures required.
2. Medium threat bushfire prone area – requires protection from predominantly ember attack. This is covered by a bushfire attack level (BAL) rating.
3. Very high bushfire threat – covered by the Bushfire Management Overlay and requires protection from ember attack, radiant heat and direct flame contact. The Bushfire Management Overlay requires a BAL assessment AND addresses the management of vegetation, water and access in the form of a Bushfire Management Statement, known as a BMS.

The system in place allows for individuals to:

1. Obtain a free Planning Property Report
2. Use Planning Maps Online to view the BMO in an interactive format, obtain a Planning Property Report, or create your own custom map.
3. View the BMO map that is incorporated into your local planning scheme by referring to Planning Schemes Online

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2. Medium threat bushfire prone area – requires protection from predominantly ember attack. This is covered by a bushfire attack level (BAL) rating.
3. Very high bushfire threat – covered by the Bushfire Management Overlay and requires protection from ember attack, radiant heat and direct flame contact. The Bushfire Management Overlay requires a BAL assessment AND addresses the management of vegetation, water and access in the form of a Bushfire Management Statement, known as a BMS.

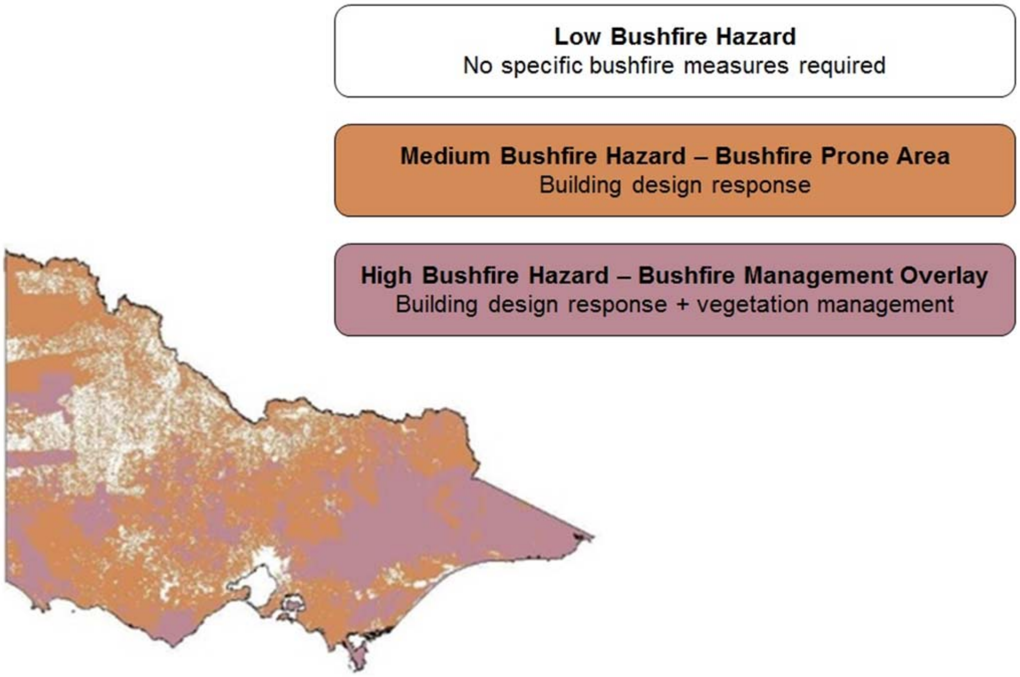


Figure 1 Victorian Bushfire Management Overlay and summary of its three categories (Source: Victorian Government, 2011a).

The BMO is part of a new multi-tiered location specific response to bushfire risk, with site based response levels increasing as bushfire hazard escalates. Low bushfire hazard areas require no additional planning measures. These are generally built up, urban areas that do not connect with the bushfire hazard, including ember attack. Areas of medium bushfire hazard, known as Bushfire Prone Areas (BPAs), are subject to, or likely to be subject to, bushfires as designated by the Victorian Minister for Planning. They cover the majority of Victoria, including grassland and farming. Development of land in BPAs has specific building requirements under the Building Code of Australia. An assessment of the site is required to establish a Bushfire Attack Level (BAL) to determine construction requirements. In establishing a site's BAL, the Fire Danger Index, vegetation type, distance of the site from vegetation and the slope of the ground under the vegetation are taken into account. Once the BAL is determined (from 'Low' to 'Flame Zone'), construction requirements are set out for things like flooring systems, external walls and doors, windows, and decks. As the bushfire threat increases, so do the construction requirements.

For land with high bushfire hazard, the BMO, covers a smaller area than the BPA (refer to Figure 1). This is considered to have the highest bushfire risk. Both building and planning responses now apply to development on this land. Based on the site assessment approach used by the AS3959 the BMO shows the defendable space, construction requirements, water supplies and access requirements that must be maintained for the life of the development.

3 Study Area

3.1 Considerations for study area selection

There are issues arising from the review of literature and policy that will be considered when defining the project's assumptions and designing the methods. These are geographical scope, fire type, factor scope, and spatial scale.

The geographical scope of the project will inform, and be informed by, the selection of case study of a previous fire event. The core criterion for selection is that the case study should include examples of different WUI morphologies.

A further issue is the type of fire considered for the case study and subsequent risk mapping. The Forest Fire Danger Index (FFDI) is the standard Australian measure of fire weather severity and can be used using appropriate equations to predict its rate of spread, intensity and difficulty of suppression (McArthur, 1967; Luke and McArthur, 1978; Ellis et al, 2004). It is therefore an essential reference point for fire type in this project. Studies have shown that 98 percent of building loss has occurred at an FFDI above 45 and that most building losses occur in 'very intense fire weather conditions' where the FFDI is above 100 (Blanchi et al., 2010). The implication of this is that if risk of building loss is the dependent variable to be tested in the project, fire type in the high end of the FFDI range should be considered.

Factor scope refers to the complex mechanisms that affect property risk in a fire event. Leonard (2009) summarises this complexity in terms of mechanisms of bushfire attack on buildings, and factors which affect building survival. The attack mechanisms that can lead to building ignition are ember attack, radiant heat, flame, wind, and convective heat. In response, the chance of a building surviving a bushfire is determined by a combination of factors including terrain, vegetation, weather, the building's location relative to other combustible elements, the building's design and maintenance, and human behaviour. This project focuses on settlement patterns and their relationship to fire risk, but this is one element in a much larger set of factors. Another question for the research design is therefore which of these factors will be included as independent variables, and which can be controlled for.

The spatial scale of analysis also requires consideration. Risk to property in a fire event could be examined at a dwelling, street, block, subdivision or settlement level. Depending on the variables included, it may be possible to define and measure independent variables at different spatial scales. For example, terrain (slope) or built material (if available) could be recorded at dwelling level, while road access, dwelling density, and subdivision morphology could be recorded at a subdivision or settlement level. The dependent variable, risk to property from a fire event, will also need to be defined and measured at an appropriate spatial scale. At a subdivision level, for instance, fire effect could be defined as the percentage of dwellings burnt within a set boundary, or the distance the fire penetrated from the 'edge' of the subdivision.

All of these considerations will be constrained by the availability and quality of data. Existing data should, where possible, be validated by independent sources of data if not already done so. The extent of the area affected by the bushfire event and the resolution of data will dictate the appropriate scale of the analysis.

3.2 Selection of the Case

The Black Saturday 2009 bushfire event saw the most significant loss of houses in Australia in the last 100 years. Of the towns affected by the bushfire and the availability of detailed data, Bendigo was assessed as a potential site to focus this case study. The City of Greater Bendigo is a main regional city in central Victoria. It is located approximately 150 km from Melbourne. Bendigo has a large urban population, being the fourth largest population in the state, as well as significant rural hinterland. A significant proportion of the city is allocated to national parks, regional parks, reserves or bushlands. Much of the rural land is used for agricultural purposes, including poultry and pig farming, sheep and cattle grazing and vineyards. There is some industrial land use in the suburbs around the central business district (CBD). The region affected by the fire that occurred 7 February 2009 occurred approximately 6 km west from the Bendigo CBD in the suburb of Maiden Gully. Maiden Gully is predominantly rural with central parklands and a dense urban and commercial region in the east and south. The area of analysis includes all primary dwellings (houses, factories) that exist on blocks where one or more houses were affected by the fire (see Figure 2). Of the total 642 dwellings analysed, 84 were damaged and 558 were undamaged. Dwellings considered as damage range from low damaged to completely destroyed. The fire burned through gently rolling country bordering the city's western suburbs, where there are numerous former gold diggings that are now public open space interspersed between suburban blocks.

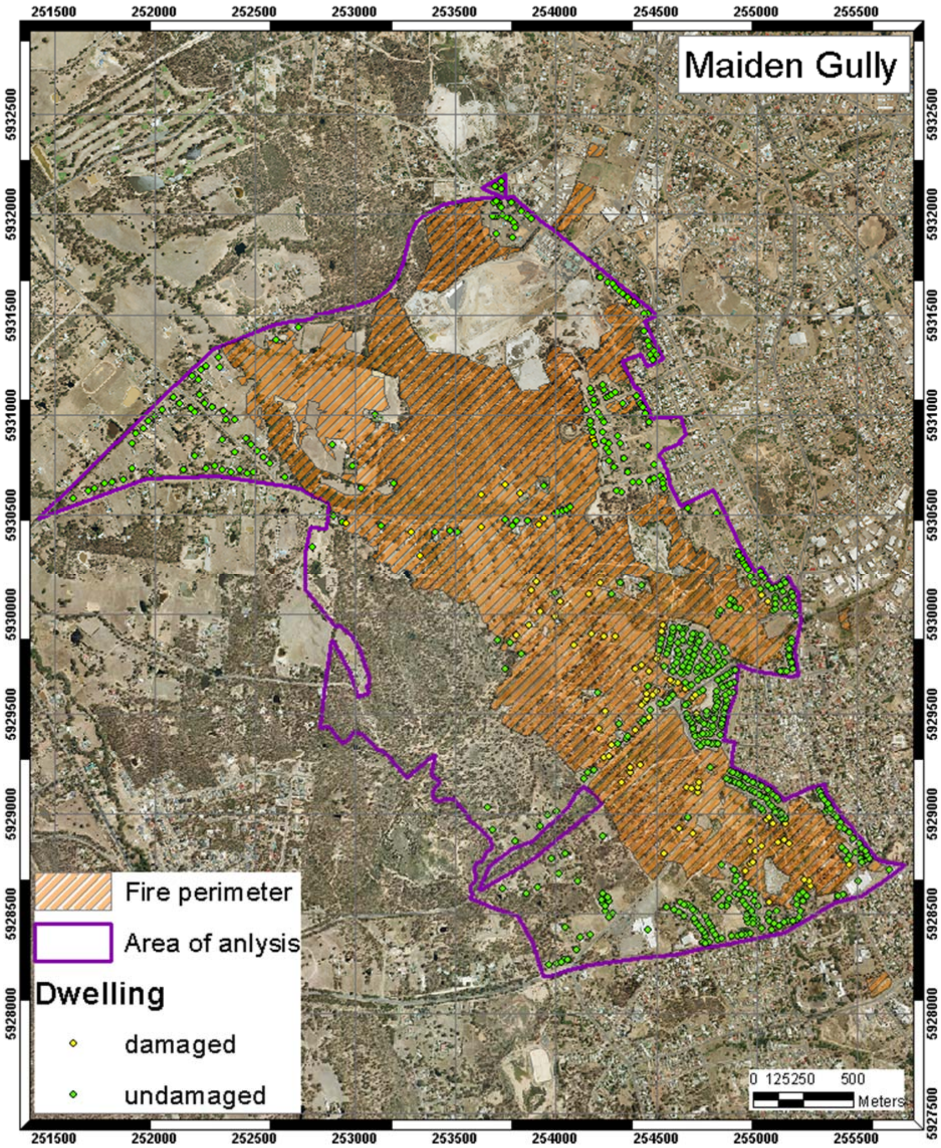


Figure 2. Area of interest and fire perimeter

3.3 Description of Bendigo Fire Ground – Vegetation and Topography

The predominant vegetation cover in Maiden Gully is exotic grasses, mostly in the north and west. Pockets in the north east and most of the southern regions are covered by scattered trees and shrubby vegetation. The central western region is mostly heathy dry forest. The remainder contains smaller pockets of ironbark and forests and woodlands, yellow box and grey box woodlands, melaleuca woodlands, spiny rush and pampas grass. Approximate coverage of these vegetation types can be observed in Table 4 and their distribution through the region in Figure 3. This region also includes areas where prior fuel reduction (2006) and more recent fuel reduction (4 months prior) had been performed. These areas may also be observed in Figure 3.

Table 4. Vegetation categories and approximate coverage

Vegetation type	Approximate Area (ha)
Exotic grass	252
Scattered trees and shrubs	214
Heathy dry forest	105
Ironbark forest	38
Recent fuel reduction	29
Yellow box and grey box forest	9
Ironbark tree cover	8
Prior fuel reduction	7
Yellow box and grey box woodland	5
Pampas grass	5
Spiny rush	4
Melaleuca	4

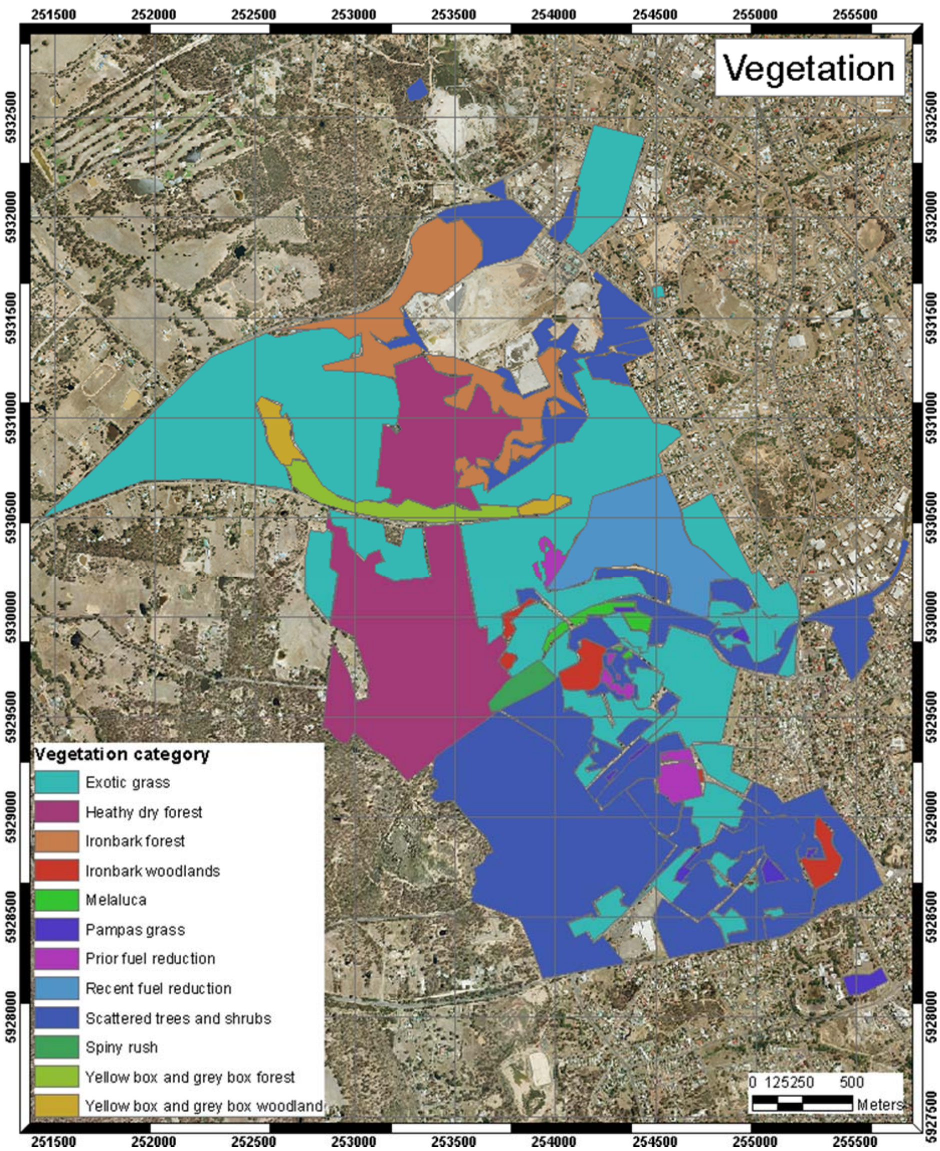


Figure 3. Distribution of vegetation classes

The relatively small areas of Ironbark Forest were generally 10-15m tall, and areas of Heathy Dry Forest were to 5-9 m tall. Similarly small areas of forest with a dominant over-storey of Yellow Box/Grey Box growing in the creek line adjacent to Taylor Street were 7-10 m tall, and the small area of Yellow Gum dominated tree cover was to 15 m tall. These treed areas are without understorey shrubs and supported only scattered grassy fuels or sparse leaf litter. The pampas grass was observed at 2m in height.

The topography of Maiden Gully consists of rolling hills at an elevation of between 192 and 283 meters above sea level. A 1 second (approximately 30m) digital elevation model (DEM) was sourced from Gillant (2011). The DEM is derived from data captured from the Shuttle Radar Topography Mission (SRTM). The product also includes slope and aspect of the terrain, determined from the DEM (Figure 4).

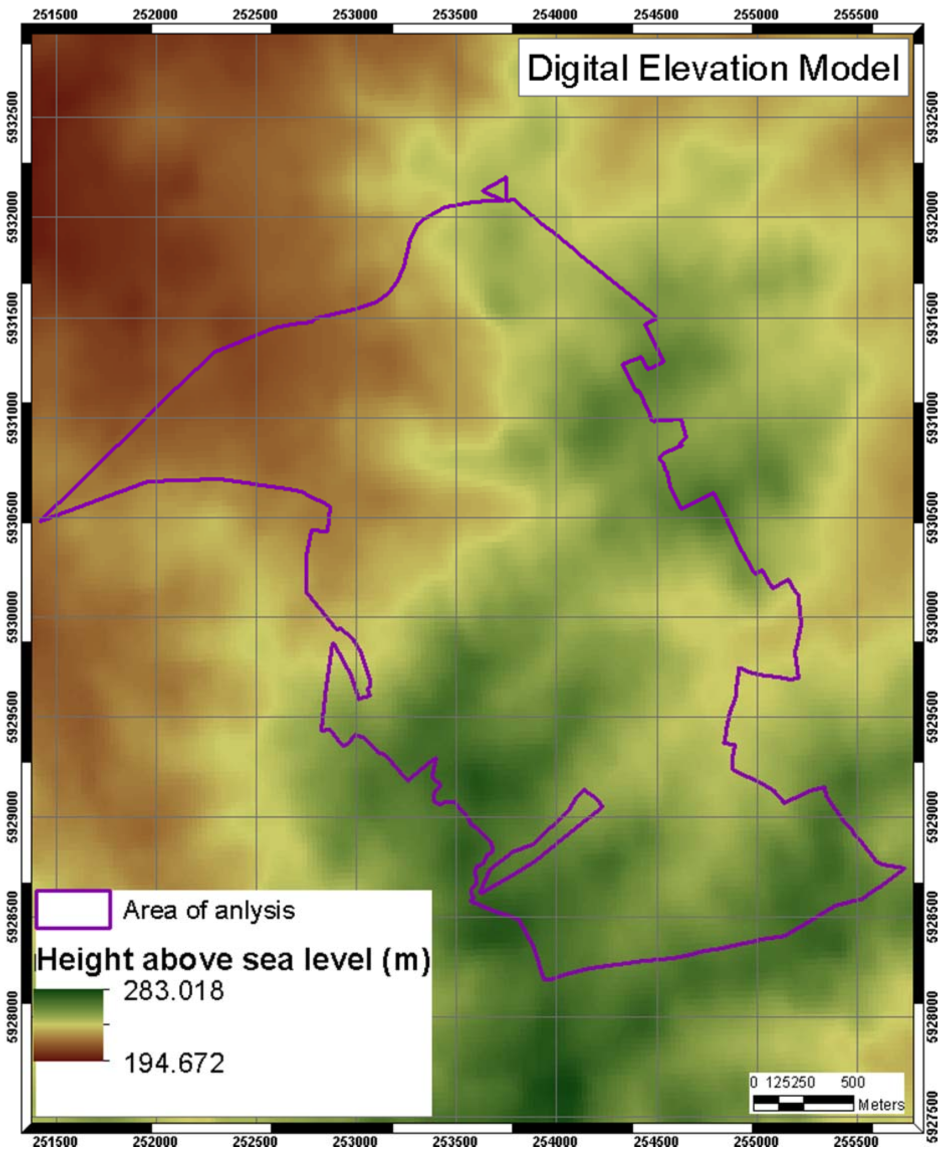


Figure 4. Digital elevation model

3.4 Description of Bendigo Fire Ground - Urban Morphology

The Maiden Gully fire ignited under suspicious circumstances in a gully close to the southern side of Bracewell Street at approximately 4:20pm on 7 February 2009. The fire burned for approximately 4 hours, running for approximately 5.5 kilometres to the south-east before the wind changed at about 18:45 which pushed the flames to the north-east, further into suburban Bendigo (see Figure 5). About half of the area burnt was public land. One fatality occurred, a number of people were injured, and 84 houses were damaged or destroyed.

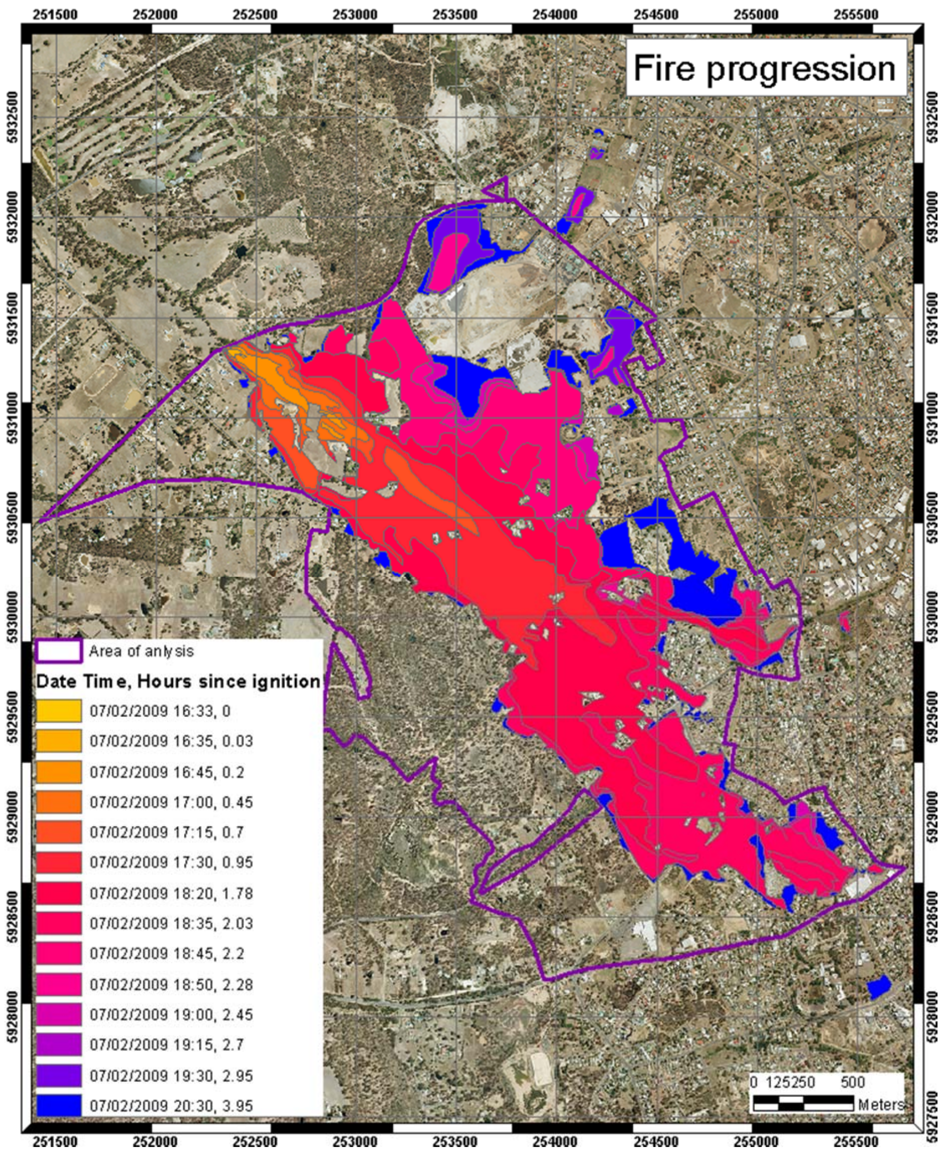


Figure 5. Fire progression

The conditions on the day of the fire are summarised from the 2009 Royal Victorian Bushfire Commission in below in Table 5.

Table 5. Summary of climatic and fire danger index conditions

Maximum temperature	The maximum temperature recorded was 45.4°C at Bendigo automatic weather station
Minimum relative humidity	The minimum relative humidity recorded was 6 per cent at 13:16
Wind	The maximum winds recorded before the wind changed to north-westerly at 41 kilometres an hour at 17:01 The maximum winds recorded after the wind change were south-westerly at 35 kilometres an hour at 18:45
Fire danger index	The maximum Grassland Fire Danger Index was 129 at 13:31

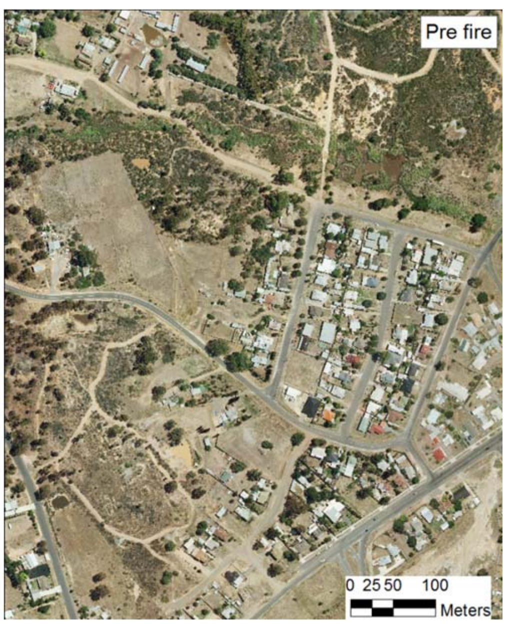
The lack of understorey fuel in treed areas provided little impediment to fire spread during the initial stages under the influence of a strong north westerly wind. While these areas may have burnt with reduced intensity, embers were still generated from burning bark, and surrounding areas of higher fuel. This fire lacked intensity overall but spread rapidly. It is unclear how much urban fuels in close proximity to dwellings contributed to the fire. In urban environments, these fuels can play a significant role in the development and spread of unplanned fires on the urban edge and into suburbs.

4 Data

4.1 Pre and Post-fire Imagery

Pre fire high resolution visible multispectral (blue, green, red) airborne imagery for the Shire of Murrindindi was made available through DEPI. The data was acquired during 2006, 2007and 2008 by United Photo & Graphics. The image used in this analysis was captured 6 January 2008 and includes 3 visible bands at a spatial resolution of 15cm, and has been fully orthorectified and tiled.

Post fire visibly airborne imagery was commissioned by the Victorian Police immediately following the February fires over key areas where human impacts were greatest. The DEPI also commissioned colour infrared data (blue, green, red, near infrared) to be collected over all fire affected areas and this was acquired during the months following the fires. All post-fire imagery was recorded at a spatial resolution of 15cm, and has been fully orthorectified. The imagery used for this analysis was captured 10 February 2009. Figure 6 shows a small subset of this imagery near the corner of Albert Street and Sparrowhawk Road, Maiden Gully.

a) 

b) 

Figure 6. Subset of pre and post fire high resolution aerial imagery captured at 15cm on a) 6 January 2008 and b) 10 February 2009. Both images being true colour (red, green, blue)

4.2 Structure Locations and Attributes

Surveys were conducted by field teams to record detailed aspects of structures within all fire affected areas. This includes the geographic coordinates of residential structure centroids and observations of the level of damage, the structure type and building materials. Subsets of these data were extracted for this study. To ensure a higher degree of accuracy for data associated with this analysis, GIS vector files describing the structure footprints (the bounding box which defines the spatial extent of structures) were also defined manually using both the pre-fire and post-fire imagery.

Structures could generally be clearly seen and delineated in the pre-fire airborne images. Structure damage was apparent in the post fire images and helped to validate survey data. Cross checking between the two images was performed to ensure that no errors or omissions were present.

Each house was attributed with a structure type (house or outbuilding) and a damage class (damaged, undamaged). Houses with any degree of damage were classified as damaged. This provided a variable that is dichotomous in nature and preserves the fact that in almost all cases houses that commence ignition do not have the capacity to extinguish themselves through any other means than external influence, such as property defence. Attributing these structures was done through subjective assessment of the pre and post-fire imagery. A single building was generally selected per property as the likely residential building. Factors influencing the decision included the size, location within the lot and roof type (gable etc). Other buildings within the property were assigned as outbuildings. Burnt buildings were generally obvious through analysis of their change in appearance between the pre and post-fire imagery. Structure outlines, including outbuildings, can be seen with the attributed dwelling centroid in Figure 7.

In general, the location of field surveyed residential structure centroids and the delineated housing footprints within Maiden Gully aligned well. The number of housing footprints delineated using the imagery (672 structures, 84 damaged) was significantly more than those captured in the survey and identified 11 structures which were damaged in addition to the survey data. Presumably this can be attributed to the selective nature of the survey. 1353 outbuildings were also collected and ranged from small sheds to large commercial and agricultural warehouses. The nature of the survey was to identify those structures most impacted by the fire whereas this study is interested in a neighbourhood analysis and thus would capture many more houses.

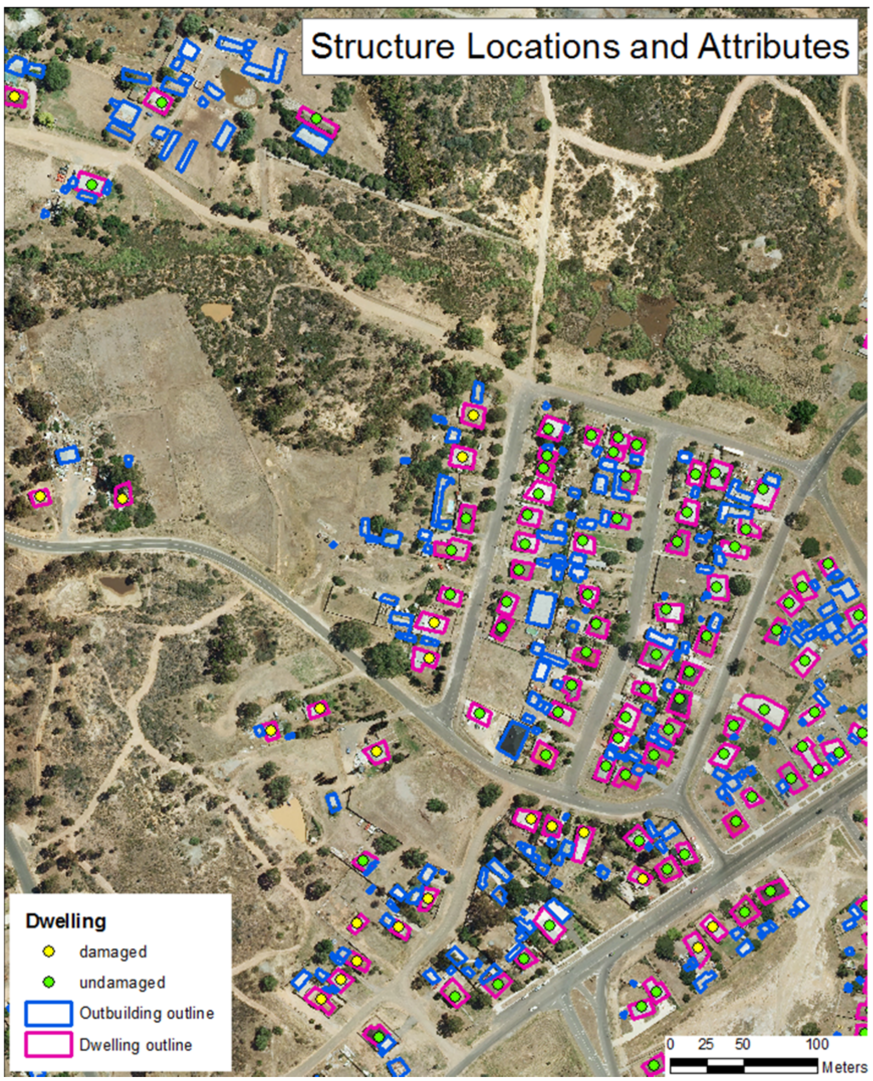


Figure 7. Structure locations and attributes

4.3 Lot footprints

Lot footprints were acquired from Vicmap portal operated by the Department of Environment and Primary Industries (DEPI). This dataset provided the GIS locations of lots and their land use (agriculture, commercial, industrial, parkland or residential). This dataset aided in the derivation of planning indices such as the site index.

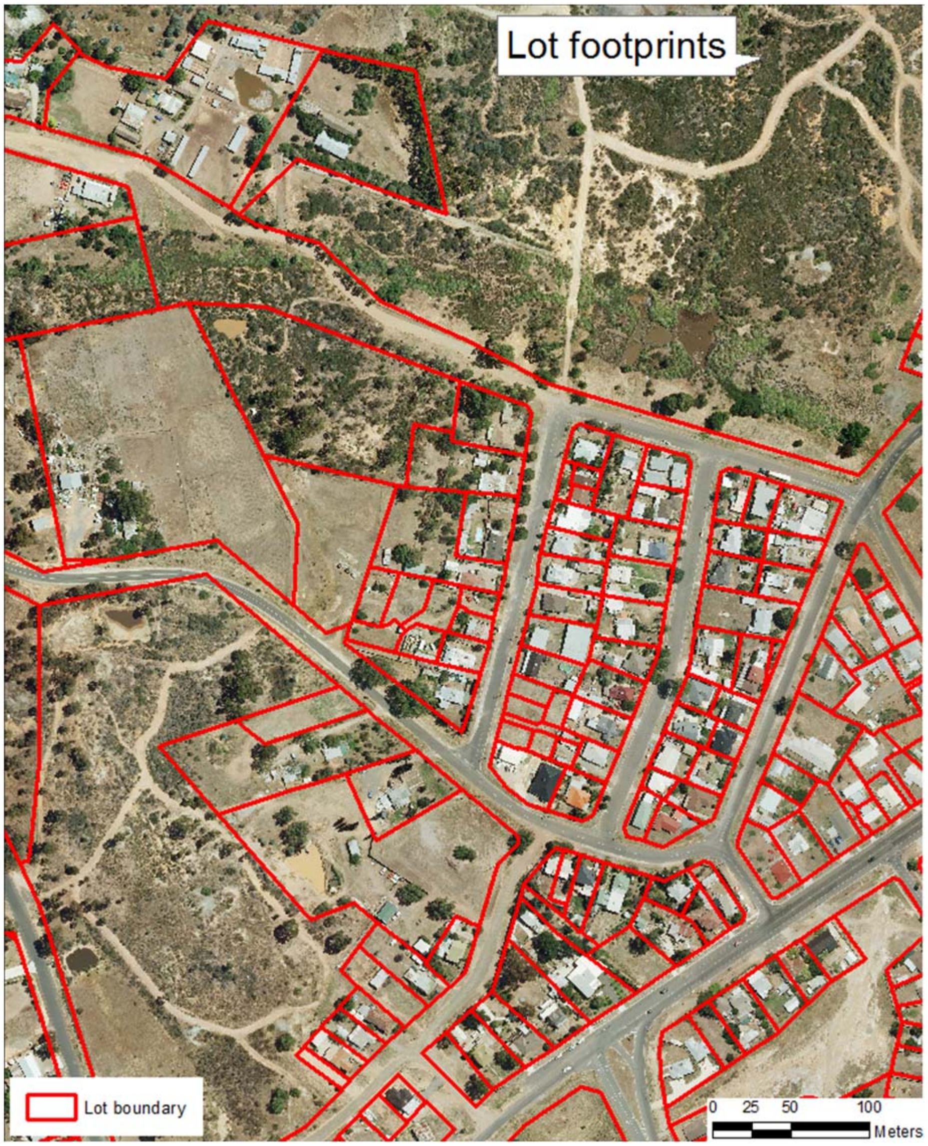


Figure 8. Department of Environment and Primary Industry (DEPI) lot footprints

4.4 Fire Isochrones

The progression of the Bendigo fire was described in detail by Goonan (2010) and fire arrival times mapped using a series of isochrones. Spline interpolation was used to produce a continuous fire arrival time surface from these isochrones at a spatial resolution of 1 m. This surface, shown in grey scale in Figure 9, indicates the time in hours (*t*) on 7 February that the fire arrived at points in the landscape.

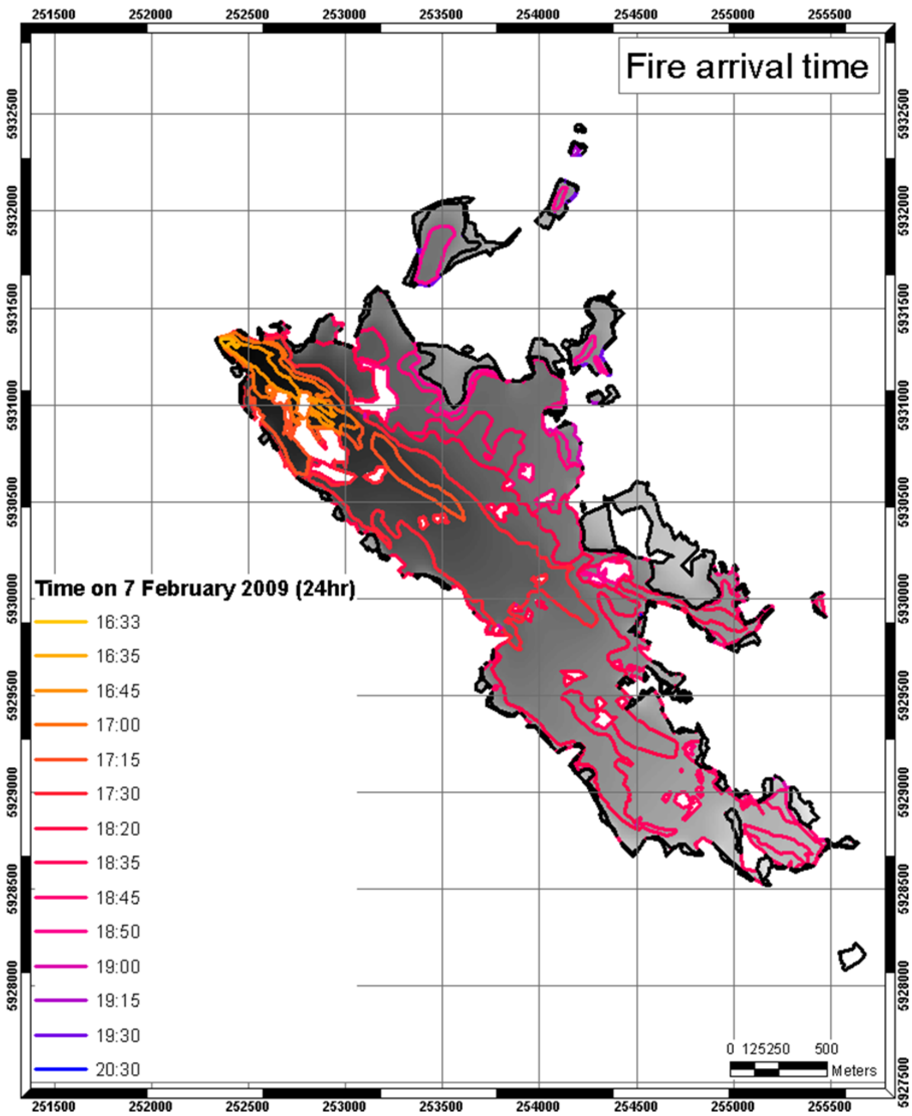


Figure 9: The progression of the Bendigo fire as defined by isochrones produced by Goonan (2010) overlayed on the interpolated fire arrival time surface. The legend expresses 24 hour time

Fire spread direction can be used to assess the specific fuels and topography that influenced the fire as it impacted a specific home or out-building. The derivation of a continuous fire direction surface can be achieved using methods similar to topographic aspect determination (e.g. Burrough and McDonnell, 1998). In this case, fire direction φ is determined from the fire arrival time surface $t_{x,y}$ using the equation:

$$\tan(\varphi) = \frac{(t_{x-1,y-1} + 2t_{x,y-1} + t_{x+1,y-1}) - (t_{x-1,y+1} + 2t_{x,y+1} + t_{x+1,y+1})}{(t_{x+1,y-1} + 2t_{x+1,y} + t_{x+1,y+1}) - (t_{x-1,y-1} + 2t_{x-1,y} + t_{x-1,y+1})}$$

where subscript *x* refers to the pixel easting coordinate and subscript *y* refers to pixel northing and φ is expressed in radians.

4.5 Vegetation Classifications

A number of sources of vegetation classification produced by state and national agencies were explored and did not provide adequate information on the nature of the vegetation in Maiden Gully. While the vegetation classifications produced by Goonan (2010) was of good spatial resolution and provided vegetation structural attributes, it did not cover the extent of Maiden Gully that the analysis was hoping to evaluate. The pre fire high resolution aerial imagery aided in extrapolating the data to the full analysis area.

5 Methods

5.1 Houses per hectare

Structure locations were used to determine the density of houses. A layer was produced of the number of structures per hectare (see Figure 10). This information can be used to determine if house densities played a role in whether or not a property was damaged by the fire.

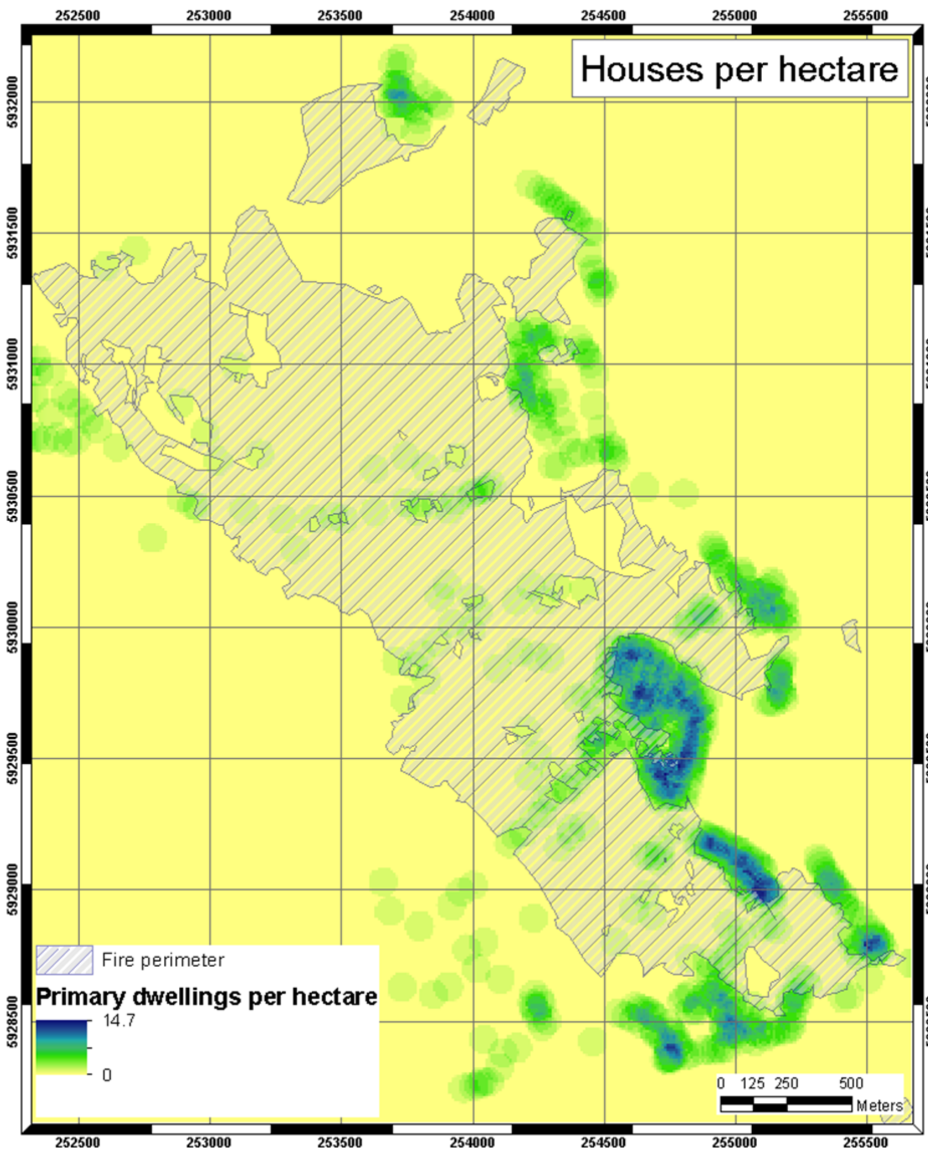


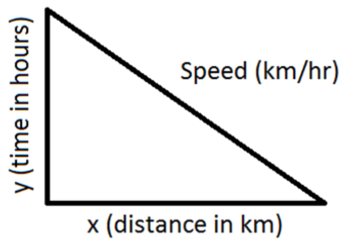
Figure 10. Density of primary structures calculated as houses per hectare

5.2 Site ratio

Lot boundaries and structure footprints were used to determine the site coverage index across the area of analysis. Site coverage index is equal to the sum of all of the footprint areas (structures and out buildings) within a lot divided by the lot area. Two outliers exist in this data and were found to be large commercial buildings that spanned more than one lot. These buildings were undamaged.

5.3 Fire arrival time, rate of spread and direction

The distance from ignition in kilometres and the time since ignition in hours were used to calculate the observed speed of the fire using simple trigonometry. By treating the isochrones as height contours a spline surface was generated at 1m x 1m. Distance from the ignition point was generated as a surface, attributed with kilometres. The slope for every pixel in the surface was calculated using trigonometry (as seen in Figure 11) and average 0.44 km/hr (Figure 12). The aspect of this surface in turn describes the direction of the fire (Figure 13).



$$\text{Speed} = \sqrt{x^2 + y^2}$$

Figure 11. Calculation for determining the speed of the fire from the isochrones.

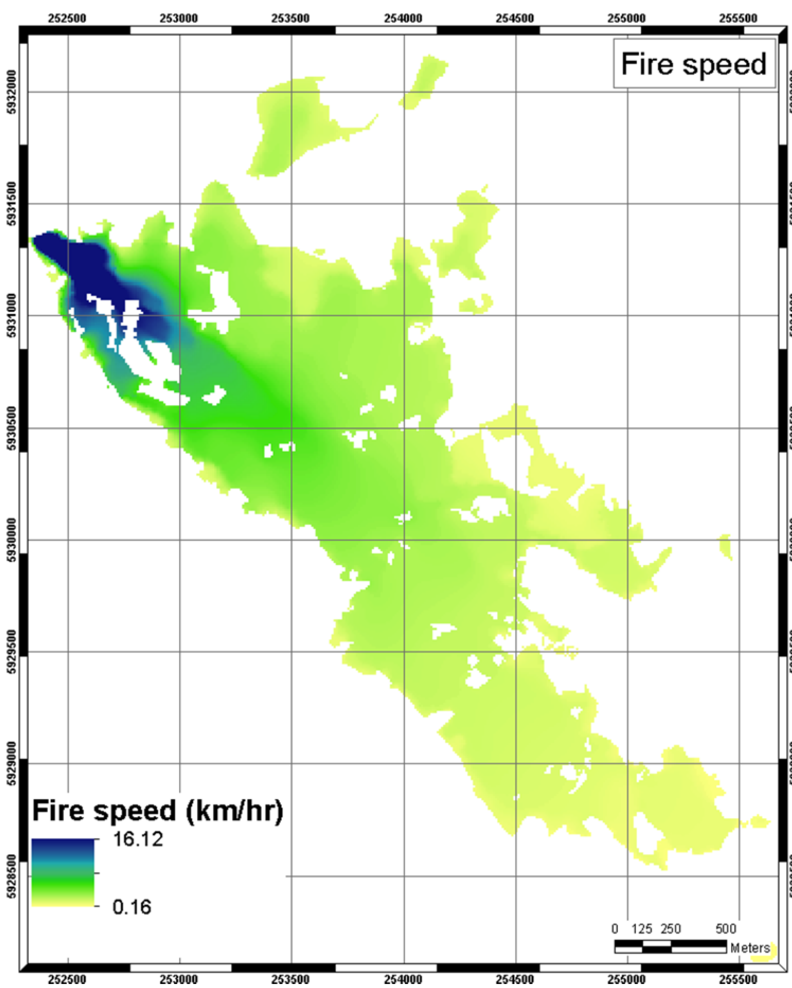


Figure 12. Fire speed in kilometres per hectare derived from fire isochrones.

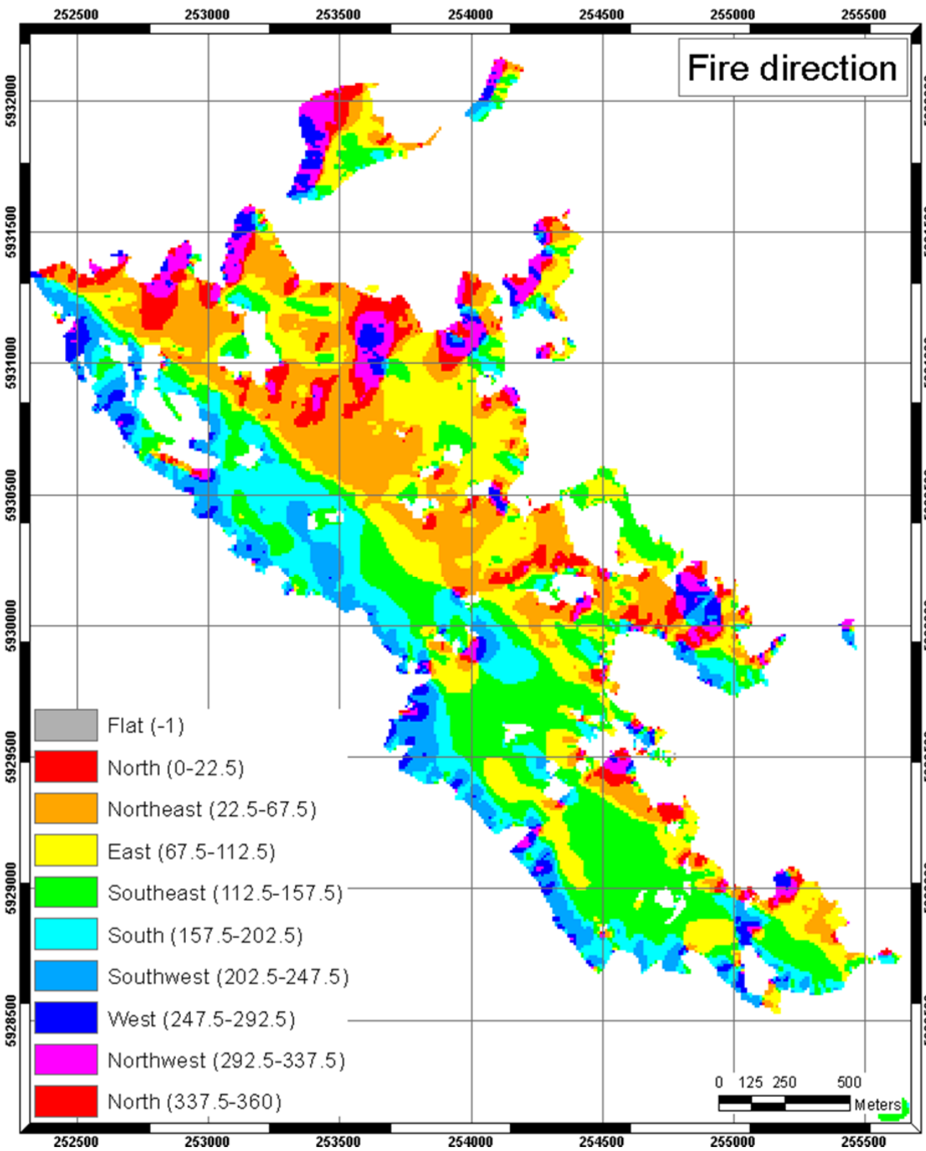


Figure 13. Fire direction derived from fire speed surface generated from fire isochrones.

Modelled fire progression is available through calculating the rate of spread (ROS). A number of methods exist for determining ROS for different vegetation types. ROS is used in other fire behaviour models, such as for fire intensity and flame height (Byram,1959, McArthur, 1973).

Due to the nature of the forested areas and the fire observed, where sparse understorey was observed and the nature of the fire being low quick moving, Nobel et al.'s (1980) equation for ROS was determined as being most appropriate.

The AS3959 uses Nobel's equation in the case of grassland ROS modelling:

$$R = 0.13 \times GFDI$$

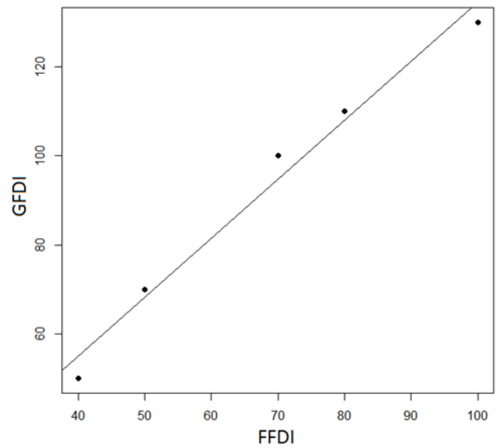
, where *R* is the rate of spread in (km/hr) and *GFDI* is the grassland fire danger index. *FFDI* was observed on the day of the fire to be 129. A relationship established by *FFDI* and *GFDI* by Purton (1982) (see Table 6) allows for a conversion, giving us a *GFDI* of 172.8.

Table 6. Grassland Fire Danger Index values equivalent to Forest Fire Index determined by Purton (1982)

FFDI	GFDI deemed equivalent by Purton(1982)
40	50
50	70
70	100
80	110
100	130

Given these values the following linear relationship was established between the two variables:

$$GFDI = 1.930 + (1.325 \times FFDI)$$



ROS transfers from being a constant spatial variable to a spatially contextual variable (Figure 14) through applying a slope correction, giving R_ϑ:

$$R_\theta = R^{0.069 \times \theta}$$

, where *R* is the rate of spread, 0.069 being a coefficient derived by McArthur (1977) and θ is the terrain slope in degrees. The 1 second (approximately 30m) SRTM slope product (Gillant, 2011) was used.

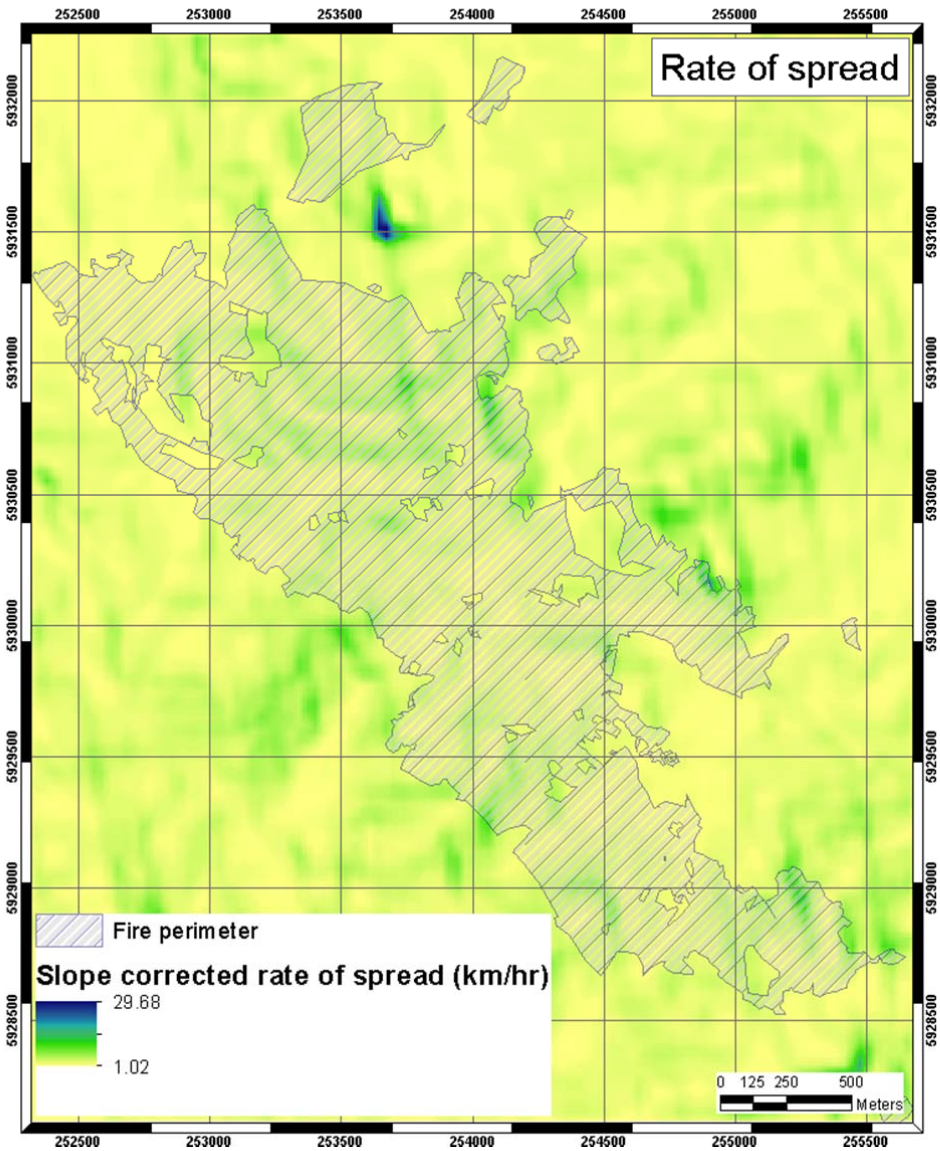


Figure 14. Slope corrected modelled rate of spread (ROS)

5.4 Fuel Load

Fuel loads were assigned to the vegetation classification using the categories outlined in AS3959 (Standards Australia, 2009), see Table 7. As the nature of the fire was low intensity it was determined that the fuel load appropriate to the analysis was surface fuel load (see Figure 15).

Table 7. Fuel load in tonnes per hectare for vegetation classes based on AS3959

Vegetation type	Surface fuel load (tonnes/ha)	Total fuel load (tonnes/ha)	AS3959 fuel type
Exotic grass	4.5	4.5	Grassland
Scattered trees and shrubs	8	8	Shrub and heath
Heathy dry forest	8	8	Shrub and heath
Ironbark forest	15	25	Woodland
Recent fuel reduction	2	2	Reduced grassland
Yellow box and grey box forest	15	25	Woodland
Ironbark tree cover	15	25	Woodland
Prior fuel reduction	3	3	Reduced grassland
Yellow box and grey box woodland	15	25	Woodland
Pampas grass	17	17	Tussock moorland
Spiny rush	8	8	Shrub and heath
Melaleuca	15	25	Woodland

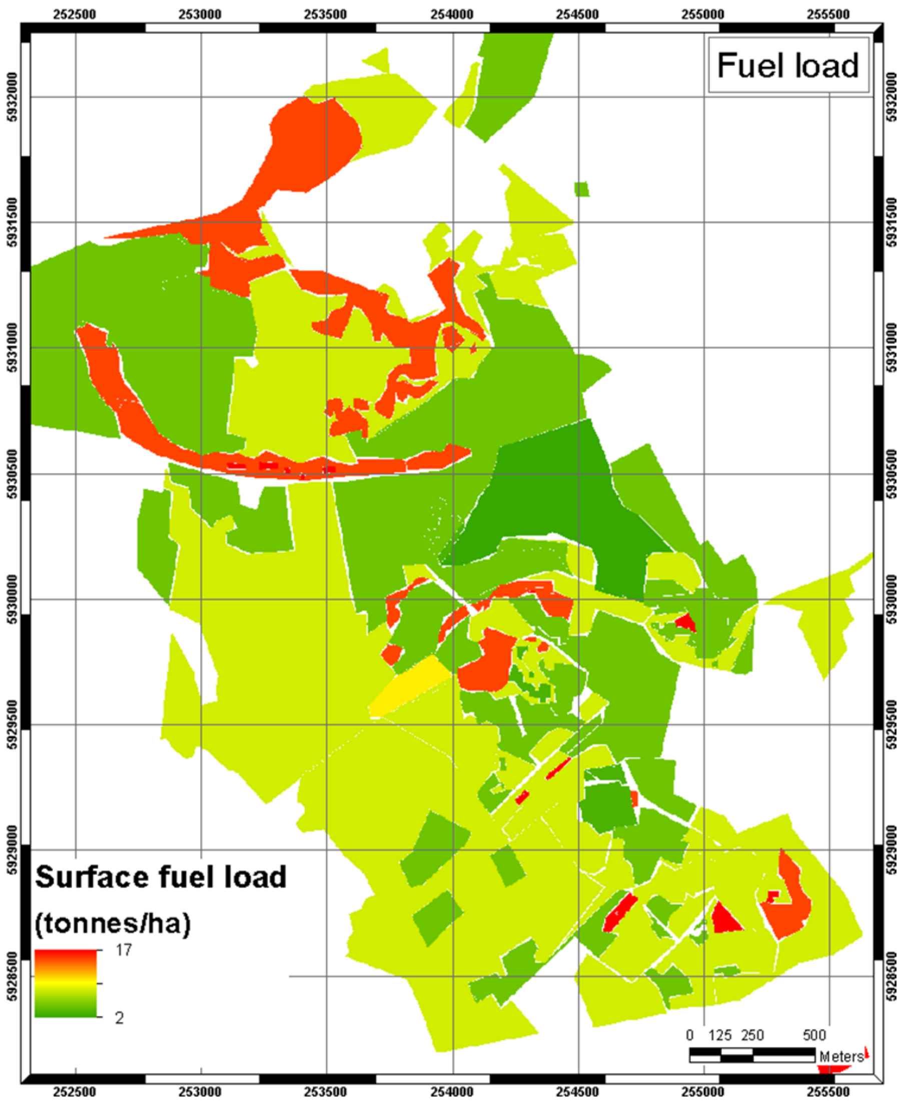


Figure 15. Surface fuel load associated with vegetation classification in tonnes per hectare

5.5 Fire line intensity

Fireline intensity is calculated from spatial inputs using the Forest Fire Behaviour model developed by A. G. McArthur and implemented in the 1977 Mk5 forest fire behaviour meter (see McArthur 1967a and 1967b). The McArthur equation can be simply represented as three key parameters; total fuel load (W), the McArthur Forest Fire Danger Index ($FFDI$) and terrain slope (θ). The McArthur Fire Line Intensity (*FLI*) is calculated in units of kW/m and is defined as being:

$$FLI = \frac{H \times W \times R_{\theta}}{36}$$

, where H is the heat of combustion (18 600 kJ/kg), W is the overall fuel load (t/ha) and R_{ϑ} being the forward slope adjusted ROS. See Figure 16 for the modelled fire line intensity.

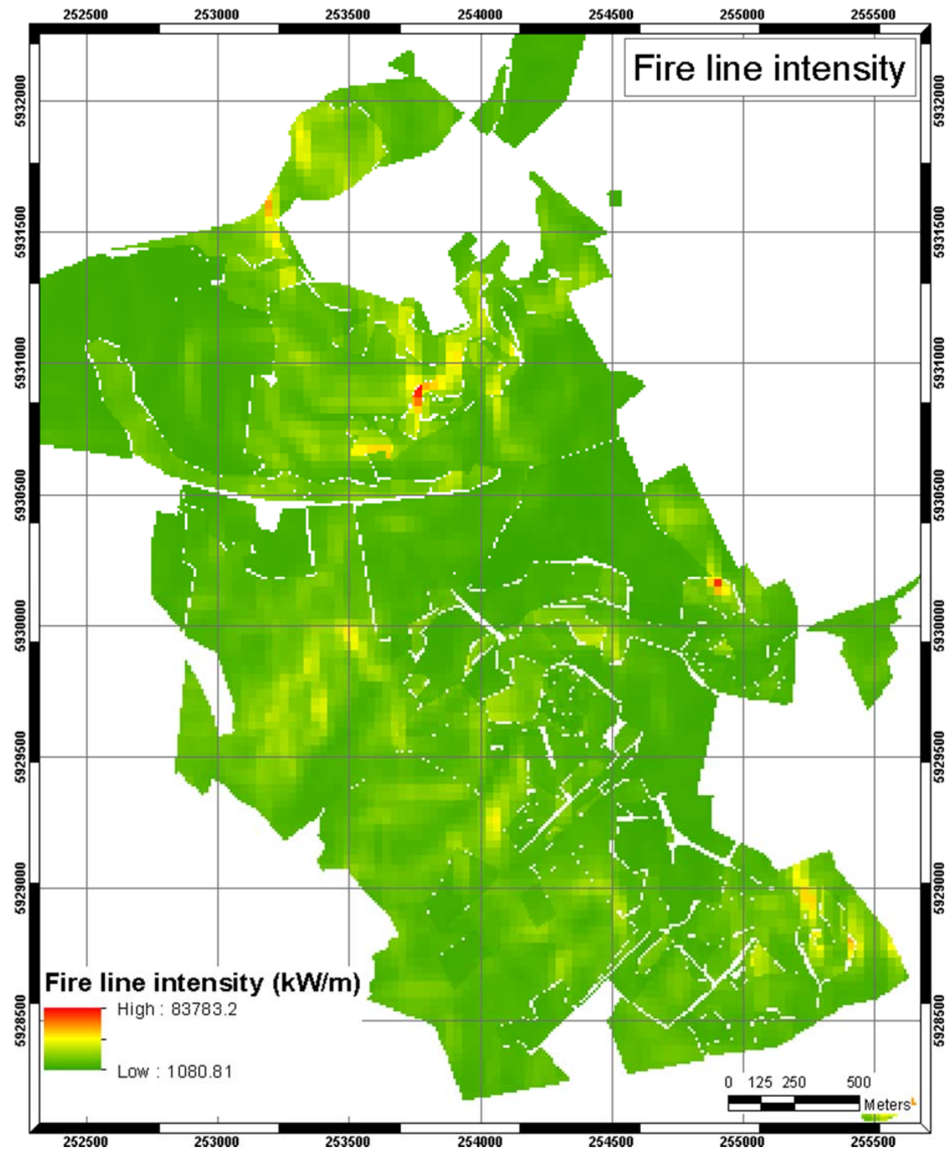


Figure 16. Fire line intensity in kilowatts per meter.

6 Analysis

The most significant factor in describing house damage is determined here by comparing known house loss to the wide range of predictor variables. This is undertaken by applying stepwise regression to minimise the Akaike's Information Criterion (AIC) of a multivariate general linear model. Tests are performed on predictor variables independently and in combination. Modelled values are assessed against observations to test their validity and predictor variables are tested for cross-correlation. To keep the approach manageable, Houses with any degree of damage are classified simply as damaged. Finally, a map of predicted probabilities may be generated by applying the model to the gridded data.

6.1 Fire spread rate analysis

If we look at house locations that fall within the fire isochrones, we can compare the derived fire speed with the modelled rate of spread. This helps us to determine whether or not the modelled rate of spread is reasonable. Elements such as wind speed and fire direction are not involved in this calculation of rate of spread. If we fit a linear model to the data we have an adjusted coefficient of determination (r^2) of 0.3 (see Figure 17). While not a great relationship between these two variables, Table 8 below shows that the data is reasonably similar.

Table 8. Statistical summary of derived fire speed (estimated using fire isocrones) and rate of spread (modelled)

Statistic	Minimum	Median	Mean	Maximum
Derived fire speed (km/hr)	1.743	3.741	3.583	4.918
Rate of spread (km/hr)	1.338	2.444	2.655	6.072

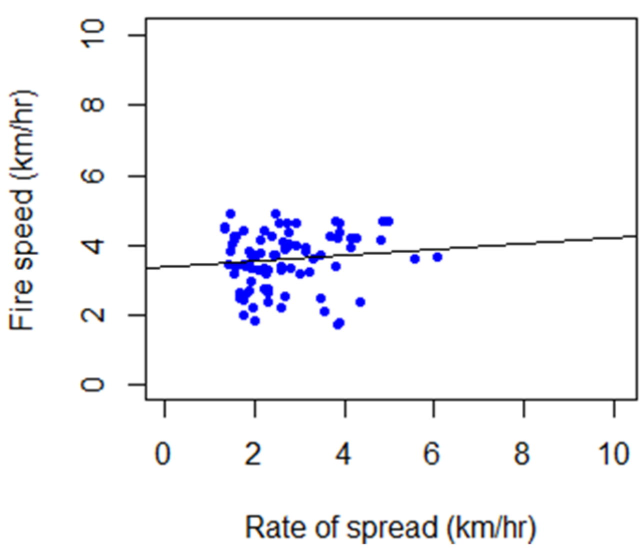


Figure 17. Relationship between derived fire speed and calculated rate of spread.

6.2 Multi-variable analysis

6.2.1 VARIABLE DEPENDENCIES

Of the data available, a number of parameters seem to offer a degree of separability between those dwellings that were damaged and those undamaged. In understanding the nature of the data the correlation matrix below (Table 9) allows us to observe the relationship (dependencies) that exists between parameters.

Table 9. Correlation matrix for candidate parameters to describe damage in the Bendigo fire.

	Elevation	Fire line intensity	Rate of spread	Site ratio	Houses per hectare
Elevation	1.000	0.298	0.123	0.058	-0.145
Fire line intensity	0.298	1.000	0.825	-0.005	-0.064
Rate of spread	0.123	0.825	1.000	-0.007	-0.059
Site ratio	0.058	-0.005	-0.007	1.000	0.342
Houses per hectare	-0.145	-0.064	-0.059	0.342	1.000

Some dependencies exist between a couple of these parameters. A strong correlation exists between rate of spread and fire line intensity (adjusted $r^2 = 0.68$), (Figure 18a), for example rate of spread is a component used the calculate fire line intensity. Understandably, site index is partially related to houses per hectare ($r^2 = 0.12$), (Figure 18b). While not significant, further inspection of the data indicates that there are a small number of outliers; the properties identified in section 5.2. This relationship describes the nature of houses in closer proximity filling more of their lot, and conversely that property lots generally being lower in size allows for more houses per hectare. The variation in these parameters across the scene allows for them to be assessed as being independent variables.

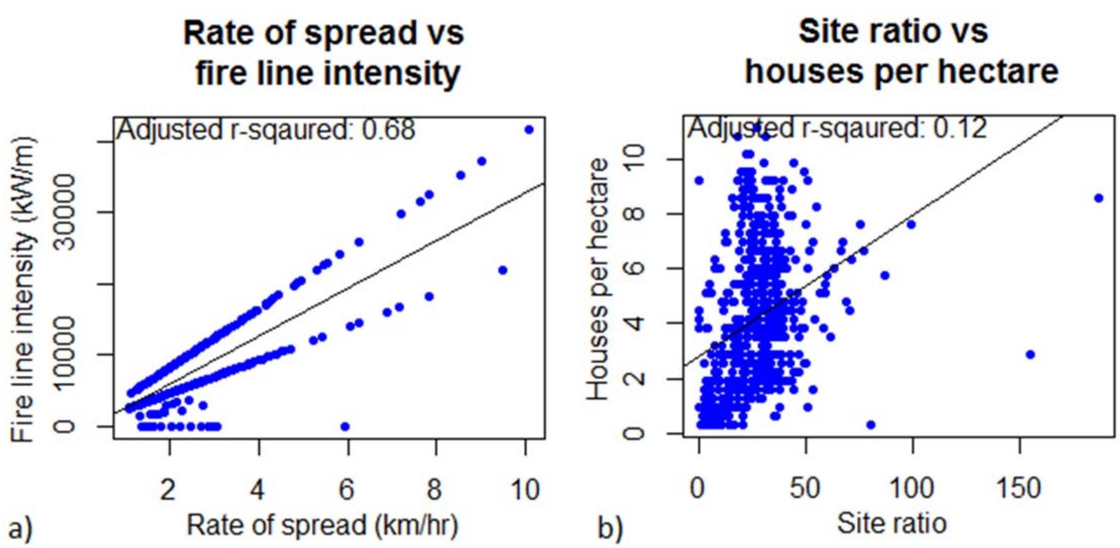


Figure 18 Correlation between rate of spread vs fire line intensity (a) and site ratio vs houses per hectare (b)

To evaluate which of these variables to use, both the predictive nature of independent and combined parameters were determined. In this case, a logistic regression is appropriate due to the categorical nature of the dependant variable, dwelling damage (i.e., binary outcome). Binary variables can be represented using an indicator variable Yi, taking on values damaged or undamaged, and modelled using a binomial distribution with probability P(Yi=1) = i. Logistic regression models this probability as a function of one or more explanatory variables. Refinement of variable selection can then be made using stepwise regression.

6.2.2 SITE FACTORS

Firstly we will observe site characteristics: height above sea level, site ratio and houses per hectare as represented in Figure 19.

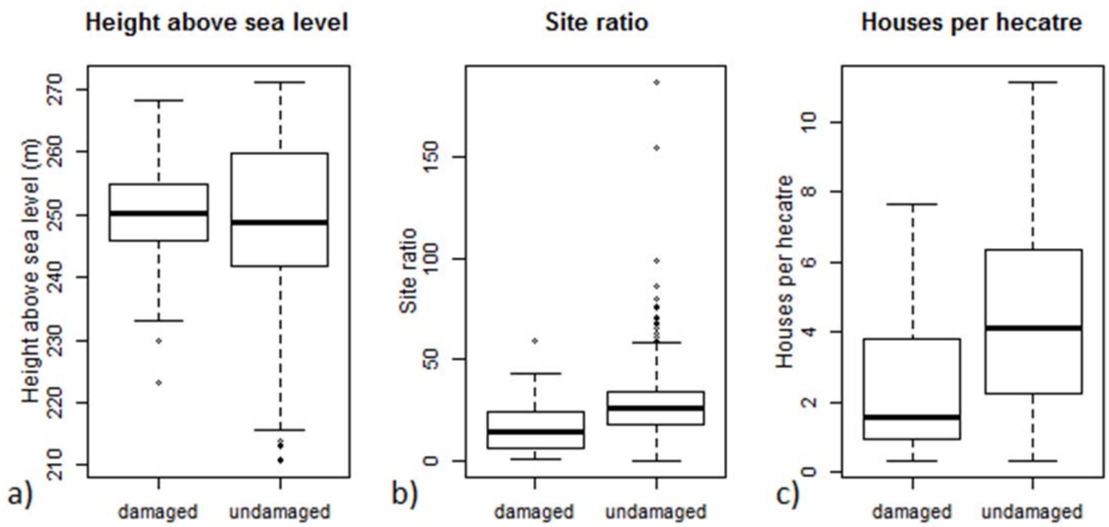


Figure 19. Distribution of a) height above sea level (m), b) the site ratio and c) houses per hectare for dwellings damaged or undamaged in the Bendigo fire.

Dwellings throughout the area affected by the fire do not seem to have any distinctive altitude (height above sea level) associate with whether or not it was damaged, just a larger range of values. Site ratio and houses per hectare seem to explain more of the difference. Sites that have a building footprint that fills most of the lot were less likely to be damaged. Areas where housing was denser in terms of the number of houses per hectare were also less likely to be damaged. The predictability of these three data to individually determine damaged from undamaged dwellings can be observed in Table 10. Elevation does not strongly discriminate between damaged and undamaged dwellings. Houses per hectare is a more significant predictor but has a higher standard error when describing dwelling damage and site ratio shows a small standard error and high significance.

6.2.3 FIRE CHARACTERISTICS

Next we assessed the modelled fire characteristics for each dwelling. The distribution of ROS and FLI can be seen in Figure 20. From this we can observed that the only discriminating characteristic of the ROS or FLI is that the range of values is greater for undamaged dwellings.

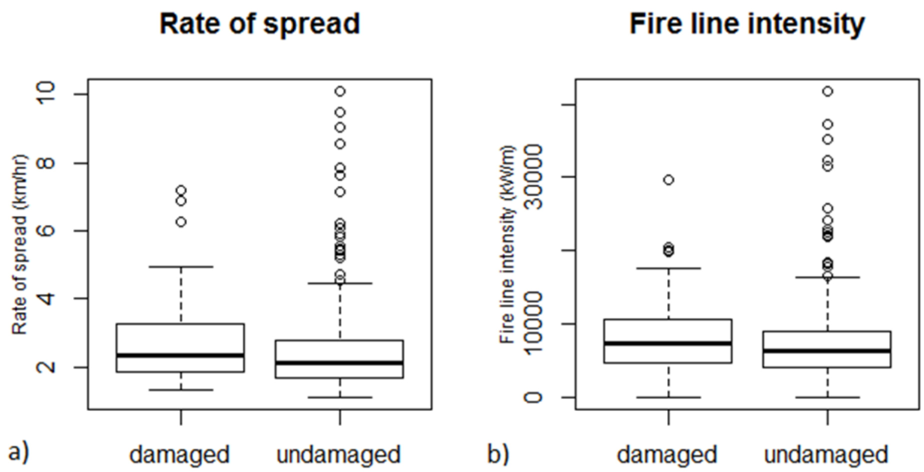


Figure 20. Distribution of a) rate of spread (km/hr) and fire line intensity (kW/m) for damaged or undamaged dwellings in the Bendigo fire.

In determining the significance of ROS and FLI in predicting the damage of a dwelling it can be noted that neither are very significant. The highest standard error exists for when using ROS as a predictor of damage even though it shows great significance.

6.2.4 COMPARISON OF ALL VARIABLES

The Akaike information criterion (AIC) supports the observation that 'houses per hectare' is the best descriptor (lowest value) followed by site ratio.

Table 10. Statistics describing the significance of variables when ingested into a general linear model

Variable	AIC		Standard Error	Pr(>|z|)
Elevation	502.0804	intercept	2.58E+00	3.02E-01
		coefficient	1.03E-02	7.66E-01
Site ratio	457.6821	intercept	2.21E-01	1.27E-02
		coefficient	1.05E-02	1.24E-09
Houses per hectare	451.4771	intercept	2.05E-01	3.69E-03
		coefficient	6.30E-02	5.30E-10
Rate of spread	498.6106	intercept	2.46E-01	7.79E-21
		coefficient	8.15E-02	4.82E-02
Fire line intensity	498.1388	intercept	2.05E-01	1.88E-27
		coefficient	2.03E-05	3.62E-02

6.2.5 COMBINED VARIABLES TO PREDICT THE LIKELIHOOD OF HOUSE DAMAGE

Individually, these variables are fairly weak at explaining dwelling damage so combinations were assessed. Using variable products, ordered by significance, and stepwise regression we can minimise the AIC to 437.99 with the following model for the probability of loss ($\log it(y)$):

$$\log it(y) = -0.59 - 0.27H - 0.03S + 5.47FLIe^{-5}$$

,where *H* is the houses per hectare, *S* is the site index and *FLI* is the fire line intensity (kW/m). From this we can say that the lower the houses per hectare and site index, and higher the *FLI* the greater the probability of loss (Figure 21). The significance of *S* and *H* was far greater than using the *FLI on its own* (Table 11).

Table 11. Modelled probability of loss coefficient details

	Estimate	Std. Error	Pr(>|z|)
(Intercept)	-5.95E-01	2.80E-01	3.34E-02
H	-2.79E-01	7.15E-02	9.60E-05
S	-3.78E-02	1.17E-02	1.18E-03
FLI	5.48E-05	2.24E-05	1.44E-02

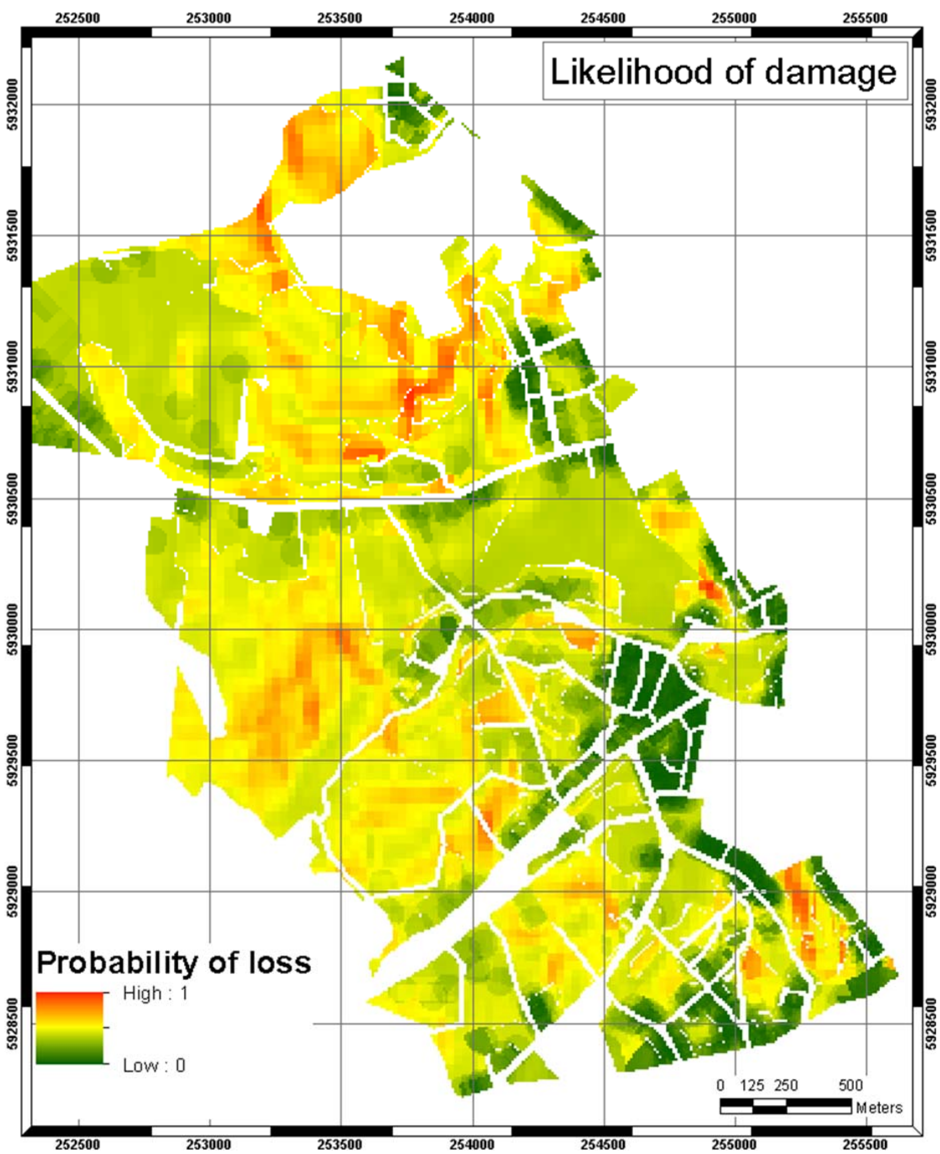


Figure 21. Probability that a dwelling will be lost in the area of analysis

7 Discussion - implications of findings & further research

7.1 Bendigo as a Bushfire Transitioning into Urban Morphology

The case study examined in this research provides an example of a bushfire interacting with an urban system (Burton et al. 1993, p. 32) in a wildland-urban interface (WUI). In this case, vegetation varied across the site. Exotic grasses predominated in the north and west, with areas of scattered trees in the north east. Scattered trees and shrubby vegetation existed in the southern parts, while the central western region contained mainly heathy dry forest. The remainder of the study area contained smaller pockets of ironbark and forests and woodlands, yellow box and grey box woodlands, melaluca woodlands, spiny rush and pampas grass.

The urban components of this landscape consisted of a range of densities from large lots often described as "rural lifestyle" through to relatively typical suburban lots approximately 800 square metres in size. While all lots are served by roads, the street network is correspondingly denser as lots sizes decrease to suburban morphologies. These urban forms are intermingled with vegetated areas (Radeloff et al., 2005; Theobald and Romme, 2007), and exist on a wider continuum between areas that are predominantly vegetated while containing some housing structures, to predominantly urban forms with limited vegetation. This intermingling can be understood in the context of increased pressures for urban growth on the edges of cities and towns, potentially increasing bushfire risks (Cottrell & King, 2007, p. 25; Theobal and Romme 2007).

This study offers useful insights when two main features are considered together. Firstly, the report describes bushfire risks as interactions with urban morphology within a particular bushfire landscape. In a wider sense, this contrasts with common fire prevention or emergency response and suppression perspectives (cf Avalapati et al. 2005, Radeloff et al. 2005, Stephens 2005). These approaches tend to take vegetation and urban form as static settings, rather than as being potentially modified in the long term.

As set out in the literature review, risks have previously been identified with particular urban morphologies in other studies. These include large or homogenous subdivisions with long interface edges, narrow streets and poor access and exit points (Cottrell & King, 2007, p. 25; Lowe et al., 2008, p. 22), particularly as densities increase (Cova 2005, p. 100). Other risks include urban riverine, ridge top forest and urban bushland as bushfire risk factors (Cottrell & King, 2007, p. 25). In this study, while the vegetation included diverse elements, the key element generating the transition to urban structures was primarily grasslands. In addition, this study describes these features in detail.

Secondly, and flowing from the points made above, this study describes the progress of the fire through the landscape temporally, including fire line intensity as a function of speed and fuel load. This allowed the research to directly inform bushfire risks to structures as a function of urban morphology within the wider landscape. This perspective offers the potential for improved design of human settlements in existing and future areas. While the study directly acknowledges the characteristics of the particular WUI in which it is placed, it goes on to identify fundamental elements in the urban morphology that are significant in terms of risks to structures, taken up in detail in the following sections.

7.2 Fuel Reduction Burns and Perimeter Roads

Fuel reduction and vegetation management regimes represent an established element of ongoing bushfire risk management in Australia and overseas. This reflects strong evidence that distance to vegetation and to higher fuel loads generally reduce risks to property and life (Chen & McAneney, 2004, p. 1); Crompton et al. (2010, p. 309); Newnham and Siggins et al. (2012). Additionally, the existence of perimeter roads provides multiple benefits, for example Callaghan et al (2010, p. 58) in addition to separation and fuels reduction, such as defensible space and access to response agencies Leonard (2009). However, in this particular instance under these weather conditions, analysis indicates that fuel reduction burns and natural breaks such as roads were ineffective at limiting the progress of the fire and did not significantly modify rates of observed losses. While considerable caution is appropriate in interpreting these findings, it appears likely that the nature of fire transmission to structures in this case was predominantly grass fires and embers. In addition, the observed outcomes are likely to also be influenced by the relative ease of access for response across the fire ground due to low levels of obstructive vegetation in many parts combined with relatively flat terrain. This interaction is not well documented in this fire hence its influence cannot be easily interpreted or predicted.

7.3 Houses per hectare and site ratio

Previous studies have highlighted density as a risk factor, but this has typically been oriented to highlighting in broad terms the risks of placing greater numbers of people in risky areas (Cottrell & King, 2007, p. 25) as population density. Cottrell and King acknowledge the diversity of characteristics to consider in WUI (2007, p. 23) there is a need to develop themes around particular built form morphology's risk factors. Urban planning factors are undeveloped as a means to reduce house ignitions by taking into account building design, defensible space and other factors Stephens and Collins (2007).

Price and Bradstock (2013), found a 72% accuracy at predicting house loss (over 3500 houses) for the Victorian 2009 fires based on a method different to that used in this study. Price and Bradstock's study used an aggregated data set that included partial damage as "undestroyed" to analyse density in terms of assessing the proportion of forest and other houses within a radius of 50m, 100m, 200m, 500m, 1000m, 2000m, and 5000m from individual houses. They found that vegetation management can modify the occurrence of crown fire to reduce house loss, up to 1 km away from houses in some situations; and that high density of houses may increase risks of losses. However, the study concludes that the wide range of vegetation management required to achieve improved outcomes, combined with the hazard presented from nearby houses, means it may be more sensible to concentrate on modification of buildings to reduce their vulnerability.

In contrast, this current study of Bendigo has directly examined a number of urban morphology features to consider the particular characteristics of urban settlements that are able to be modified using planning controls. The analysis demonstrated that the most significant urban design factor for predicting structure damage in this case study is the number houses per hectare and site ratio, two closely related factors. In this scenario, as densities increase (expressed as dwellings per hectare) the likelihood of house losses decreases. This finding provides a more direct acknowledgement of density as a risk factor is appropriate, particularly in landscape settings analogous to the Bendigo case.

7.4 Implications for Urban Morphology and Urban Planning and Design Standards

While the analysis is scenario-specific, the findings do suggest that it may be appropriate to consider urban densities of greater than approximately 12 dwellings per hectare as safer than lower densities. It is likely that a range of built form co-variables exist, such as age of buildings, fencing types, presence of outbuildings, and the characteristics and management of gardens near to buildings. In addition, it is likely that the challenges associated with active response over large areas reduce the effectiveness of fire and emergency services as densities become lower. Further, it is likely that different settings and structure types may demonstrate different outcomes in terms of dwellings per hectare. However, in the context of continued pressures for expansion, such as those highlighted by Theobald and Romme (2007), and the possibility for infill development as settlements expand to remediate existing risks, it would appear that density could be more directly addressed in planning controls.

As set out in the literature review of this report, there is already some consistency across Australia in terms of planning policies, particularly given that AS3959 has offered a level of focus between planning systems as it is integrated with planning controls. It is also the case that many planning systems already discourage ongoing creation of rural lifestyle or semi-rural lots for a range of reasons including protection of productive rural land, vegetation protection, infrastructure cost and reduction of environmental impacts. Further, in areas where bushfire controls exist, a combination of building and planning controls do in some cases discourage or prevent construction of new structures or creation of lots where Bushfire Attack Levels exceed established limits. Notwithstanding these, it would seem appropriate to consider these at a scale beyond case by case understandings to take into account overall densities as a factor in bushfire risks.

8 Conclusion

The research has shown that higher densities represented as houses per hectare and higher site occupation leading to a reduction in loss. Other important factor is fire line intensity which provides an expected level of correlation relating higher intensities to higher loss. The most powerful predictor is the combination of these factors; a stepwise regression model has been developed that combines these factors into a single index which predicts house loss likelihood which was the key purpose of the project.

The findings suggest that it is appropriate to investigate whether similar results would be achieved when examining other scenarios that vary by vegetation types and urban morphology features. Given the ongoing pressures predicted across Australia for sustained urban growth, combined with increased desires to strengthen native vegetation controls, it is important that change is managed in such a way that ongoing development manages bushfire risks appropriately. Ongoing work in this area to build a wider knowledge base relating to urban morphology and particularly density would require that data capture we undertaken in ways that facilitate comparability across cases. In particular, data sets that include reliable and comparable information on fire progression, house loss, whether active response occurred, fencing types, fuel reduction history and vegetation prior to events. This could be augmented considerably by data that provides increased detail of emergency response locations and timing.

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