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Early evacuation is the best bushfire risk mitigation strategy for south-eastern Australia*

Tyron J. Venn and John Quiggin[†]

Given the large and increasing bushfire threat to lives and property in Australia, there is a need for economic evaluation of risk mitigation policies that can be implemented by governments and homeowners. Three broad policies applicable for existing at-risk communities are evaluated: expanded use of landscape-scale prescribed fire; home ignition zone treatment (bushfire defence sprinklers); and early evacuation when a bushfire is burning on extreme or catastrophic fire danger days. Early evacuation is the only option that yields net economic benefits relative to existing policy.

Key words: bushfire, economic efficiency, evacuation, home ignition zone, prescribed fire.

1. Introduction

Bushfire (wildfire) management is an economic problem that demands efficient deployment of limited resources to alternative risk mitigation strategies over space and time to protect a range of market and nonmarket goods and services valued by society. In addition to direct suppression of bushfire, three broad approaches to risk mitigation are practised in bushfire-prone areas of the world: landscape-scale prescribed fire or mechanical fuel treatments; home ignition zone[1] treatments on the structure and in fuels proximate to the structure; and evacuation (Paveglio *et al*. 2012; Calkin *et al*. 2014).

Economic evaluation of bushfire risk mitigation requires estimation of numerous parameters. These include the probability that bushfire will threaten assets on the landscape; the susceptibility of assets to bushfire exposure; the effectiveness of bushfire risk mitigation in terms of reducing the probability of bushfire and the susceptibility of assets to bushfire; and the cost of mitigation strategies.

Estimates have been made of some of these parameters for particular strategies in particular forests or regions (Berry and Hesseln 2004; Ager

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† Tyron J. Venn is at School of Business, University of the Sunshine Coast, Sippy Downs, Queensland, 4556, Australia. John Quiggin (email: j.quiggin@uq.edu.au) is at School of Economics, The University of Queensland, St. Lucia, Queensland, 4072, Australia.

[1] The home ignition zone, a concept developed by Cohen (2000), is defined in Australia as the area within 30 m of a home, including the structure itself.

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et al. 2007; Venn and Calkin 2011; O'Donnell *et al.* 2014; Penman *et al.* 2014). However, only limited attention has been paid to the economic efficiency of wildfire risk mitigation. Furthermore, economists investigating bushfire risk mitigation have undertaken their analysis almost exclusively at the forest scale and have yet to address the identified need for evaluations of state and national bushfire policy (Clayton *et al.* 2014; Milne *et al.* 2014).

A review of the international literature revealed only four studies of the economic performance of bushfire risk mitigation: three from the United States (Mercer *et al.* 2007; Stockmann *et al.* 2010; Prestemon *et al.* 2012) and one from Australia (Florec *et al.* 2013). Mercer *et al.* (2007) and Florec *et al.* (2013) found prescribed fire to be economically efficient in Volusia County, Florida, USA, and a synthetic landscape representative of the northern jarrah forests of south-west Western Australia, respectively. However, Stockmann *et al.* (2010) found prescribed fire and landscape-scale mechanical fuel reduction treatments to be economically inefficient in south-west Montana, USA.

Prestemon *et al.* (2012) found that landscape-scale mechanical fuel reduction treatments were economically viable in less than one per cent of treatable forestland in 12 western states of the United States when benefits of the treatments included only avoided (i) private property damage; (ii) wildfire suppression costs; (iii) timber losses; and (iv) ecosystem damage. Stockmann *et al.* (2010) evaluated home ignition zone treatments, with the most cost-effective treatment costing US$3.7 million per home loss avoided.

South-eastern Australia presents unique challenges for the design of bushfire risk mitigation policy.[2] It is one of the three most bushfire-prone regions in the world, along with southern California and southern France (Hennessy *et al.* 2005). In south-eastern Australia and southern California, the risk of severe bushfire events that threaten lives and homes is considerably higher than anywhere else in the world because of (i) the frequency of drought and high fire danger conditions; (ii) large areas of bushland; (iii) rapid rates of fuel accumulation; and (iv) large numbers of people choosing to live in close proximity to these fuels.

Australian residents proximate to bushland are three times more likely to be killed by a bushfire than their American counterparts.[3] Evidence suggests that the risk of loss of life, relative to the risk of loss of houses, is also higher in Australia than in the United States. For example, in October 2007 fires in southern California burned over 150,000 ha of drought-affected

[2] For the purposes of this paper, south-east Australia is the area south of a line that can be drawn on a map of Australia between the cities of Sydney and Adelaide. This area includes 20 million ha of bushfire-prone *Eucalyptus* forests and woodlands (Bradstock *et al.* 2012) and is home to about 15 million people, or two-thirds of the national population.

[3] The estimation of this statistic from the published literature is described in section A.3 of Appendix S1.

shrublands with wind gusts up to 100 km/h and led to the evacuation of over 300,000 people. The fires, and the policy response, resulted in the loss of 2223 homes and seven lives (McCaffrey and Rhodes 2009). In contrast, the most recent catastrophic bushfire event in Australia - the 7 February 2009 Black Saturday bushfires in Victoria - claimed a comparable number of houses (2298), but resulted in the loss of 173 lives (Parliament of Victoria 2010a,b).

Several climatic, ecological and socio-economic factors are likely to have contributed to this disparity. It is important to consider whether bushfire management policy is one of those factors. Bushfire management authorities in Australia have accumulated many years of experience implementing programs to reduce fuels in the landscape and in home ignition zones. However, large-scale, coordinated evacuation, which is considered the safest option to protect assets in North America (Stephens *et al.* 2009; Beverly and Bothwell 2011; Paveglio *et al.* 2012), has been relatively uncommon in Australia. Instead, bushfire policy in Australia places a high degree of responsibility on residents. Residents decide how to protect their homes and whether to evacuate early or stay to defend their homes.

The bushfire policy in effect at the time of the Black Saturday bushfires, described as *Prepare, Stay and Defend Your Property or Leave Early* and often shortened by the public and in the media to 'Stay or Go', was endorsed by all Australian fire services and most police forces (Australian Fire Authorities Council 2005). Rather than attempting to evacuate all those in the likely path of a bushfire, fire authorities advised residents to decide in advance of a fire whether they would prepare to stay and defend their homes or leave early (Australian Fire Authorities Council 2005).

The Royal Commission investigating the 2009 Black Saturday bushfires found many deficiencies with the 'stay or go' policy (Parliament of Victoria 2010a). For example, while discussing the option provided by Australian bushfire policy to residents to stay and defend their home, Council assisting the Royal Commission into Black Saturday, Jack Rush QC, remarked, 'what we are calling on people to do is to fight fires in situations where we would not put our most experienced firefighters' (Parliament of Victoria 2010b). Nevertheless, the national bushfire policy in effect at the time of publication, 'Prepare. Act. Survive.', continues to allow residents to choose to stay and defend, while putting greater emphasis on leaving early as the safest risk mitigation strategy (ACT Emergency Services Agency 2009; Harrap 2010; Australian Fire Authorities Council 2012; Whittaker *et al.* 2013).

The purpose of this paper is to estimate the economic performance of three bushfire risk mitigation policies for south-eastern Australia. These are expanded use of landscape-scale prescribed fire; sprinkler systems as a home ignition zone treatment; and early evacuation when a bushfire is burning on extreme and catastrophic fire danger days. The first two policies improve the defendability of homes and are compatible with existing bushfire policy that allows residents to stay and defend. The third is a North American-style evacuation policy. This paper advances the bushfire economics literature by providing the first estimate of the expected net benefits of a bushfire evacuation policy, and the first comparative assessment of alternative bushfire risk mitigation policies at the state and national level.

2. Bushfire risk in Australia

Bushfires are a major socio-economic hazard in south-eastern Australia. They accounted for 39 per cent of natural disaster deaths and 57 per cent of natural disaster injuries between 1967 and 1999 (Bureau of Transport Economics 2001). Between 1900 and 2010, bushfires killed approximately 750 people and destroyed more than 11,000 homes (Blanchi *et al.* 2010; Haynes *et al.* 2010). Nevertheless, many Australians choose to live in high-bushfire-risk areas, and contemporary urban expansion is increasing the proportion of housing stock in these areas (Crompton *et al.* 2010).

In most Australian states, fire weather risk is quantified using one of two indices: the Forest Fire Danger Index (FFDI) or the Grassland Fire Danger Index (GFDI) (Luke and McArthur 1978; Lucas *et al.* 2007). Under a revised fire danger warning introduced in the aftermath of the 2009 Black Saturday bushfires, index values between 75 and 100 are classified as 'extreme', while index values in excess of 100 are classified as 'catastrophic'.

Data compiled by Blanchi *et al.* (2010), Crompton *et al.* (2010) and Haynes *et al.* (2010) revealed that 78 per cent of house loss and 79 per cent of life loss due to bushfire in Australia have occurred when the FFDI was at least 75 and that six catastrophic (FFDI ≥100) events since 1939 account for 60 per cent of all life and house losses. All of these events were associated with severe fire weather (above 99th percentile) conditions resulting from a combination of strong winds, high temperatures, low relative humidity and an extended drought period, which made direct suppression of the fire front impossible (Blanchi *et al.* 2010; Bradstock *et al.* 2012). Climate change is expected to increase the frequency of extreme or catastrophic bushfires in Australia this century (Hasson *et al.* 2009; Intergovernmental Panel on Climate Change 2014).

Residents and homes within 100 m of bushland account for approximately 90 per cent of losses from bushfires (Chen and McAneney 2004; Crompton *et al.* 2010). There are about 550,000 addresses (6 per cent of the national housing stock) within 100 m of bushland, over half of which are in the Greater Sydney region (McAneney *et al.* 2009). Based on the Australian average household occupancy rate of 2.6 (Australian Bureau of Statistics 2011), about 1.43 million people are at risk.

Simple averages of historic life and house loss data may be misleading indicators of contemporary bushfire risk in Australia, because catastrophic bushfires are infrequent and the level of development in bushfire-prone areas has increased substantially over the last century. Adjusting the historic time series of bushfire house losses and fatalities in Australia to estimate losses that would have occurred under the societal conditions of 2008–2009, Crompton *et al*. (2010) found the 'normalised' annual levels of home loss and fatalities to be 301 and 14, respectively.

Therefore, the average annual probability that a home within 100 m of bushland will be destroyed by bushfire is 1 in 1800, and the average annual probability that a resident within 100 m of bushland will be killed by bushfire is 1 in 102,000. To put these normalised risk levels in perspective, residents at risk of bushfire are almost 10 times more likely to die in a vehicle accident than in a bushfire, and almost twice as likely to experience a structural fire ignition, as to experience a bushfire that destroys their home (Trewin 2006).

Bushfire fatality data from 1900 to 2008, and for the Black Saturday bushfire of 2009, indicate that 45 and 77 per cent of fatalities, respectively, are known to be people who (for various reasons) did not evacuate. By contrast, 32 and 17 per cent of fatalities are known to have died during late evacuation between 1900 and 2008 and during the Black Saturday bushfires, respectively[4] (Handmer *et al*. 2010; Haynes *et al*. 2010).

Evidence from investigations following Black Saturday suggests that around 40 per cent of the at-risk population chose to evacuate. Of this group, over 50 per cent, or nearly 25 per cent of the population, evacuated late and incurred 29 deaths (Handmer *et al*. 2010; Whittaker *et al*. 2013). On the other hand, the nearly 60 per cent of the total who did not evacuate suffered 132 deaths.[5] The risk of death was therefore around twice as high among those who did not evacuate, compared to those who evacuated late.

3. Quantification of benefits and costs of bushfire risk mitigation in south-eastern Australia

In this section, we present an analytical framework for the evaluation of bushfire mitigation policies. We focus on annual risk, mitigation cost and effectiveness estimates appropriate for south-eastern Australia as a whole in order to evaluate state-level policies. The analytical approach is applicable more broadly, but we will not consider extensions beyond south-eastern Australia.

The expected annual net benefit, $E(NB_i)$, of bushfire mitigation policy i with respect to the status quo is estimated as

[4] For consistency, statistics reported for Black Saturday from Handmer *et al*. (2010) are those derived on page 33 of that report by applying the fatality codes of Haynes *et al*. (2010). The percentages of fatalities who did not evacuate and who evacuated late do not sum to 100 because other fatalities include people who were travelling through the area unaware, camping, bushwalking or whose activity at time of death is unknown.

[5] Late evacuation and nonevacuation fatalities do not sum to 172, because 5 per cent of fatalities were from the Other category, including bushwalkers and campers.

$$E(NB_i) = \left[\sum_{j=1}^{N} p_j e_{ij}\left(A_j V_j\right)\right] - C_i, \quad (1)$$

where p_j is the status quo annual probability that bushfire destroys asset j within 100 m of bushland, A_j is the number of units of asset j at risk within 100 m of bushland, V_j is the economic value of one unit of asset j, e_{ij} is the effectiveness of bushfire risk mitigation policy i in protecting asset j, which can take on values between -1 (100 per cent increase in risk) and 1 (complete risk reduction to zero), and C_i is the annual cost of bushfire risk mitigation policy i, which is assumed to be in addition to (not in substitution of) status quo mitigation costs. The terms within the square brackets estimate annual avoided (or, for negative values, increased) losses associated with bushfire risk mitigation policy i. If $E(NB_i)$ is positive, avoided losses exceed the costs of mitigation, indicating the policy is economically efficient relative to the status quo.

In this paper, we account for bushfire impacts on human life and private homes. Three alternative bushfire risk mitigation policies are compared to the status quo:

1. Prescribed fire: enhanced landscape-scale prescribed fire program that burns 2 M ha (10 per cent) of bushfire-prone forests in south-eastern Australia each year;
2. Sprinklers[6]: a home ignition zone (HIZ) treatment policy that reduces the probability of structure loss by requiring installation of bushfire defence sprinkler systems on all homes within 100 m of bushland; and
3. Early evacuation: evacuation of all residents within 100 m of bushland when a bushfire is threatening[7] and the FFDI is forecast to be at least 75.

Each policy targets a different component of bushfire risk, namely the likelihood and behaviour of bushfires on the landscape, the probability of structure ignition given a bushfire threat, and the probability of civilian death. In practice, these three policies could be integrated but independent analysis is also appropriate because, with increasing fuel treatment around the home, the HIZ becomes more independent of fire behaviour in surrounding forest (Calkin *et al.* 2014), and the effectiveness of early evacuation on extreme and catastrophic fire danger weather days is largely independent of levels of landscape-level prescribed fire and treatments in the HIZ.

[6] Appendix S1 explains why sprinkler systems have been evaluated in preference to structural modifications or vegetation treatments in the home ignition zone.

[7] A bushfire is defined as ‘threatening’ if there is at least a 10 per cent probability that the fire perimeter will reach the residences in question. Households subject to this policy can be identified using spatial bushfire simulation models, such as Phoenix-SABRE (Queensland Fire and Emergency Services 2015).

Estimates for the variables in Equation (1) could be derived from spatially and temporally explicit empirical or simulated data for specific fire-prone areas. Such data are not available for south-eastern Australia. Table 1 reports the parameter values adopted to estimate the status quo level of expected annual life and house loss to bushfire. These estimates are consistent with the normalised expected annual levels of life and house loss reported by Crompton *et al.* (2010).

The value of a statistical life in Australia has been estimated at $7.1 million (Access Economics 2008, adjusted to 2012 dollars with the Australian consumer price index).[8]

The estimated unit value for houses at risk in south-eastern Australia has been derived from average market replacement values as follows. The average nominal building cost for a new house (excluding land) in Australia in 2012 was $287,000 (Australian Bureau of Statistics 2013). The average value of contents of an Australian home in 2012 was $66,000 (adjusted from 2009–2010 nominal values by the consumer price index) (Australian Bureau of Statistics 2011). Therefore, the average market replacement value of a home and contents in 2012 was approximately $350,000. Unless houses destroyed by bushfire are close to the beginning of their expected life, estimating their loss to society at their replacement value will significantly overestimate the economic loss. Bureau of Transport Economics (2001) recommended estimating the economic value of house and contents loss from bushfires at 75 per cent of their replacement value. This approach has been adopted, yielding an average house value of $266,000.

Table 2 reports the parameter values for effectiveness, unit cost and annual cost adopted for each bushfire risk mitigation policy evaluated.[9] The cost estimate for the early evacuation policy requires additional explanation. From weather data reported by Lucas *et al.* (2007), the population-weighted mean return interval for an average household in south-eastern Australia for days when the FFDI is at least 75 is 1 day every 5.6 years.[10] However, there are no data on the probability of an evacuation event – the probability of a bushfire threatening homes on a day when the FFDI is at least 75. The following paragraph explains the approach adopted to estimate this probability.

[8] Unless stated otherwise, all dollar amounts are Australian dollars. In December 2015, AU $1 = US$0.73.

[9] Appendix S1 summarises the bushfire and structure fire risk mitigation literature supporting these parameter estimates.

[10] Weather data for the period 1973 to 2007 reported by Lucas (2007) indicate that exposure of residents to these conditions varies widely throughout south-east Australia. For example, Melbourne experiences a day when the FFDI is at least 75 once every 2.8 years, and in Sydney, it is once every 5.5 years, while in Canberra it is once every 6.6 years. For the period analysed by Lucas *et al.* (2007), Hobart did not experience any days where these conditions were experienced; however, the 1967 Hobart bushfire killed 64 civilians on a day when the FFDI was 119 (Blanchi *et al.* 2010; Haynes *et al.* 2010).

Table 1 Parameter values adopted to estimate status quo bushfire risk to life and homes in south-eastern Australia

Asset at risk	Unit value (V_j, \$M)	Number at risk (A_j)	Status quo annual probability of loss (p_j)	Expected annual loss ($p_j{*}A_j$)
Lives	7.10	1,430,000	1 in 102,000	14
Homes	0.26	550,000	1 in 1800	301

The normalised expected annual level of home loss is approximately 300, the historic level of home loss within a bushfire perimeter is 30 per cent (Whittaker *et al.* 2010; Gibbons *et al.* 2012) and the historic proportion of all homes destroyed by bushfires when the FFDI is at least 75 is about 80 per cent. It follows that, in an average year, around 800 homes per annum will be within a bushfire perimeter on a day when the FFDI is at least 75. A policy which requires evacuation when the probability of such an event is 10 per cent or more will result in an expected annual number of 8000 households evacuated per year. With 550,000 homes within 100 m of bushland, this represents an annual evacuation probability of 1.5 per cent for the average household and a mean evacuation return interval of 70 years.

More conservative policies, with a bushfire probability threshold of less than 10 per cent, would result in higher evacuation rates and correspondingly higher costs. Extending the zone of mandatory evacuation beyond 100 m from bushland, for example by evacuating whole communities, would increase the number of households affected.

Records are poor for bushfires that did not destroy homes or kill civilians. Consequently, it is not possible to confidently accommodate ‘false alarms’ in the analysis of the early evacuation policy. However, bushfires burning under extreme or catastrophic fire danger conditions close to populated areas have a high likelihood of destroying homes, due to a low likelihood of successful suppression. This suggests errors associated with underestimation of evacuation triggers are unlikely to be large and can be examined using standard sensitivity analyses, which are presented below.

4. Economic performance of bushfire risk mitigation policies

Table 2 reports the economic performance of the three bushfire risk mitigation policies, relative to the status quo: additional prescribed fire; sprinkler systems; and early evacuation. These alternative policies have been evaluated in addition to status quo mitigation activities including current levels of prescribed fire.

All three policies reduce the expected annual level of life loss. Sprinkler systems and additional prescribed fire also reduce the expected annual level of house loss. Early evacuation increases the level of house loss, because residents are not defending their houses. Nevertheless, early evacuation is the only policy estimated to generate net benefits relative to the status quo.

Table 2 Economic evaluation of alternative bushfire risk mitigation policies

Bushfire risk mitigation policy	Effectiveness (e_{ij})		Unit cost ($)	Annual cost (*$m*)	Expected annual avoided life loss¶	Expected annual avoided house loss††	Annual avoided asset losses ($m)‡‡	E (NB_i) ($m)§§
	Lives	Homes						
Prescribed fire†	0.50	0.50	235/ha	423	7.0	151	89	−344
Sprinklers‡	0.54	0.54	13,000/home	322	7.6	163	96	−225
Early evacuation§	0.40	−0.40	500/home	4	5.5	−117	8	4

Notes: †The prescribed fire policy is expected to reduce bushfire probability by 50 per cent, resulting in a 50 per cent reduction in life and home loss. The unit cost of the policy has been adopted from Penman *et al*. (2011). The annual cost of prescribed fire is the unit cost multiplied by 1.8 million ha (net change in annual treated area relative to the status quo). Lower estimates, of around $100/ha, are given by Deloitte Access Economics (2014), Florec *et al*. (2013) and Penman *et al*. (2014).
‡10 per cent of residents within 100 m of bushland are assumed to have already installed bushfire defence sprinkler systems. The effectiveness of bushfire defence sprinkler systems is a 60 per cent reduction in life and house loss multiplied by the 90 per cent of homes in which sprinklers will be installed. The cost of a bushfire defence sprinkler system for a typical Australian house has been estimated by the authors at $13,000 (details on request). Annual cost is the unit cost multiplied by 90 per cent of 550,000 households, converted to a perpetual annuity with a 5 per cent real rate of discount.
§The effectiveness of early evacuation in reducing life loss is 50 per cent multiplied by the 79 per cent of fatalities that occur on days when FFDI ≥75. Effectiveness of early evacuation in reducing house loss is −50 per cent multiplied by the 78 per cent of house losses that occur on days when FFDI ≥75. The unit cost was adapted from Deloitte Access Economics (2013) for a 4 day evacuation event: $200 for the first day for an average (2.6 member) household and $100 per household per day thereafter. Annual cost is the unit cost multiplied by the 7800 expected annual evacuations.
¶The effectiveness of the bushfire risk mitigation policy in reducing life loss, multiplied by the expected annual loss of life (from Table 1).
††The effectiveness of the bushfire risk mitigation policy in reducing house loss, multiplied by the expected annual loss of homes (from Table 1).
‡‡The sum of expected annual avoided life loss multiplied by the unit value of life (from Table 1), plus the expected annual avoided home loss multiplied by the unit value of a home (from Table 1).
§§Annual avoided asset losses minus annual cost.

In Figures 1–4, we present sensitivity analyses for three model parameters. Figure 1 shows the effect of varying the effectiveness of the bushfire risk mitigation strategy. Figures 2 and 3 deal with variations in the value imputed to lives and houses saved. Figure 4 shows the effect of variations in the cost of implementing the programs.

Our main finding that evacuation is economically more efficient, is robust to these parametric variations in the sense that none of the ranges of net benefit estimates for the three mitigation policies overlap. For example, even if sprinkler systems are 90 per cent effective at saving lives and houses (a 50 per cent increase over the base case), and early evacuation is 50 per cent less effective than assumed in the base case, early evacuation yields a higher net benefit (Figure 1). If prescribed fire costs are \$80/ha (a 65 per cent decrease relative to the base case), and costs of early evacuation are 100 per cent higher than assumed in the base case, early evacuation still yields a higher net benefit (Figure 4). Similar results apply for the other parameter variations. Moreover, the additional prescribed fire and sprinkler policies are economically inefficient at all evaluated levels of effectiveness.

On the other hand, the finding that early evacuation is economically efficient, that is yields net benefits relative to the status quo, is sensitive to some parameter variations. For example, a reduction of 30 per cent in effectiveness of the policy is sufficient to render this policy inefficient, although still superior to sprinklers and additional prescribed fire.

The main disadvantage of evacuation, the increased loss of houses relative to the status quo, is classified in this analysis as a reduction in benefits (risk mitigation strategy effectiveness multiplied by asset value) rather than as a

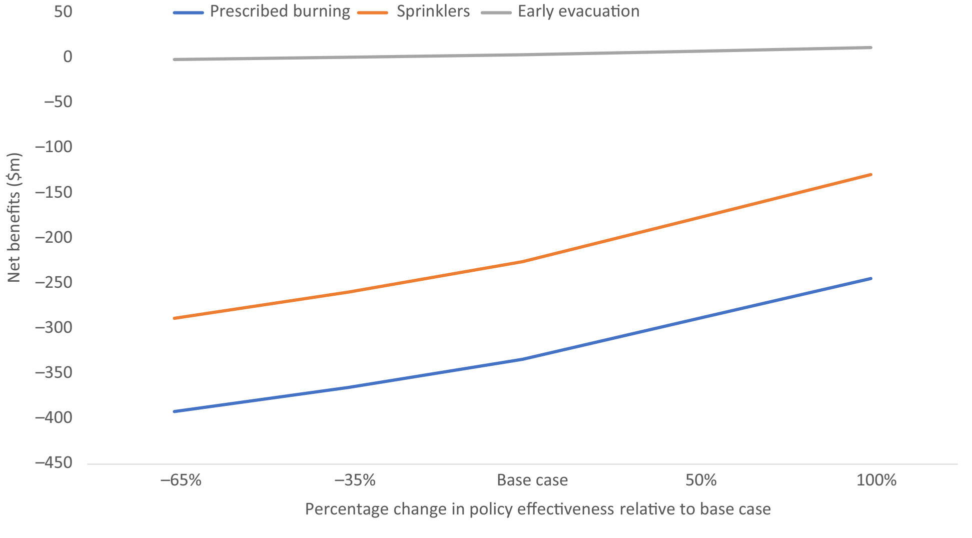

Figure 1 Sensitivity of expected annual net benefits of bushfire risk mitigation policies to the effectiveness of the risk mitigation policy. [Colour figure can be viewed at wileyonlinelibrary.com]

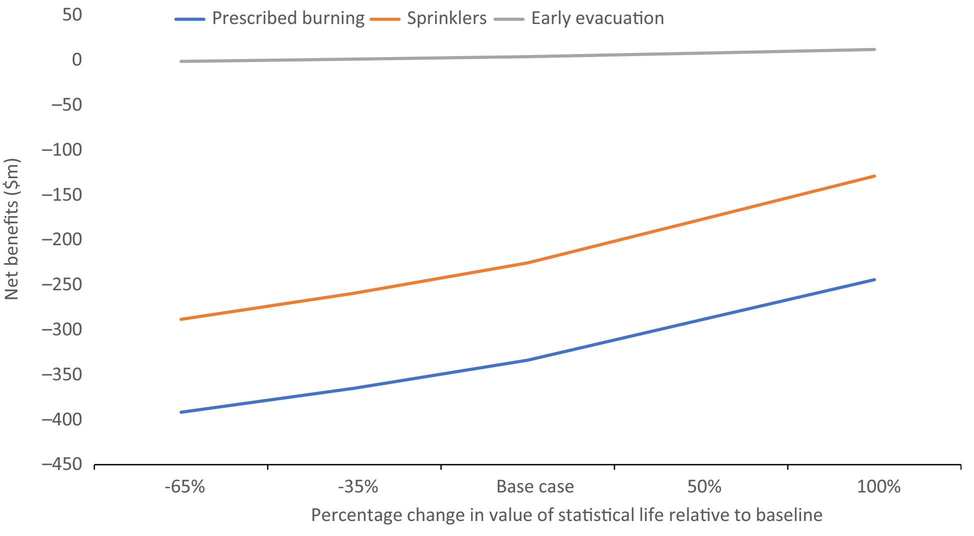

Figure 2 Sensitivity of expected annual net benefits of bushfire risk mitigation policies to the value of a statistical life saved. [Colour figure can be viewed at wileyonlinelibrary.com]

component of costs. The sensitivity of the net valuation to changes in house loss is reported in Figures 1 and 3.

As shown in Figure 4, the net benefits of the early evacuation policy are robust to changes in costs (and frequency) of evacuation. The implementation costs of the evacuation policy are relatively low such that variations in costs or frequency make only a modest difference to net benefits. Even if household evacuation costs per bushfire evacuation event are twice as high as the base case, early evacuation remains economically efficient at \$0.6 million/y. Doubling early evacuation cost is also equivalent to doubling the number of evacuation events for the average at-risk household (to one every 35 years) or doubling the number of households affected annually due to a more conservative early evacuation policy, at the base case household evacuation cost per event. If the number of evacuation events for the average at-risk household quadrupled (not illustrated in Figure 4) to 1 every 18 years, the early evacuation policy would become economically inefficient (−\$8 million/y), but remain more efficient than prescribed fire and sprinklers.

5. Concluding comments

Our conclusion regarding sprinkler systems is consistent with previous analysis which suggests that sprinkler systems designed to limit damages from structure fires do not provide a net benefit to society (Williams 1995; Poh and Weinert 2009). The probability of bushfire-caused ignition of homes within 100 m of bushland is half the probability of a structure fire ignition, but the cost of bushfire protection sprinkler systems is substantially greater than that of structure fire systems (Country Fire Service 2000).

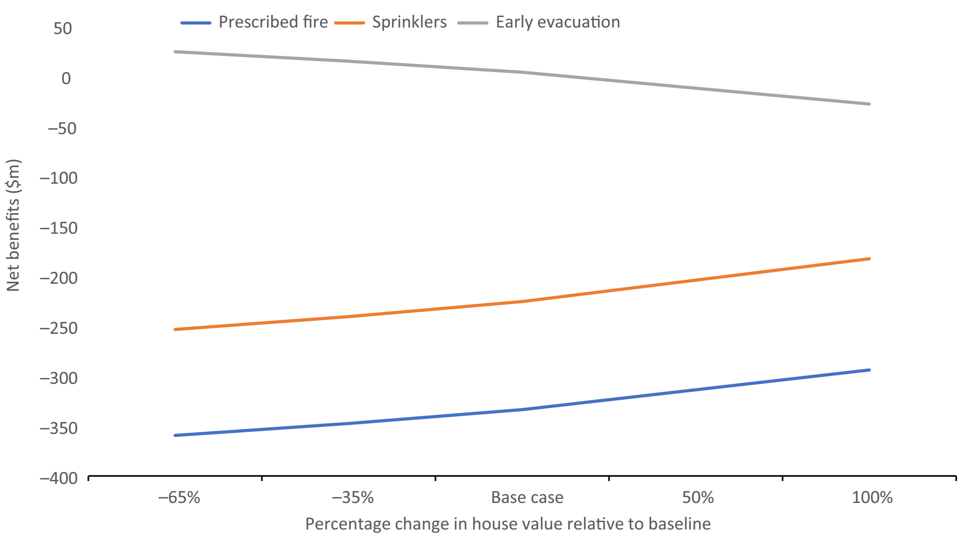

Figure 3 Sensitivity of expected annual net benefits of bushfire risk mitigation policies to the economic value of houses. [Colour figure can be viewed at wileyonlinelibrary.com]

Prescribed fire is an integral part of contemporary bushfire risk mitigation in Australia. In response to the 2009 Black Saturday bushfires, the Victorian Government committed to spend an average of $95 million each year for 4 years to increase the rate of prescribed fire to about 5 per cent of public forestland in the state each year (Victorian Government 2010). No evaluation of the expected return on this investment has been published.

Our analysis indicates that prescribed fire investments are economically inefficient in south-eastern Australia when the objectives are to reduce loss of life and homes. The prescribed fire policy evaluated here would need to generate $190/ha treated in benefits in addition to protecting life and homes, such as enhancing biodiversity conservation, before the prescribed fire policy would break even. Furthermore, there are concerns about the technical feasibility of achieving annual treated area targets of 5–15 per cent of the landscape. For example, the state of Victoria, with 7.7 million ha of bushfire-prone forests, experiences about 10 days each year with conditions considered suitable for prescribed fire (Esplin *et al*. 2003).

We now consider the economic argument against residents staying and defending homes. Those who advocate staying to defend properties point out that fatalities among residents who put up an effective defence of their home accounted for only 5 per cent of the total during the Black Saturday bushfires, and a smaller percentage of the total over the period 1900 to 2008 (Handmer *et al*. 2010; Haynes *et al*. 2010; Whittaker *et al*. 2013). However, a further 25 per cent of fatalities during Black Saturday had performed some home defence of questionable effectiveness and many more died passively sheltering throughout the fire. One-third of all fatalities during Black Saturday were associated with houses that were perilously close to bushland and were not defendable (Handmer

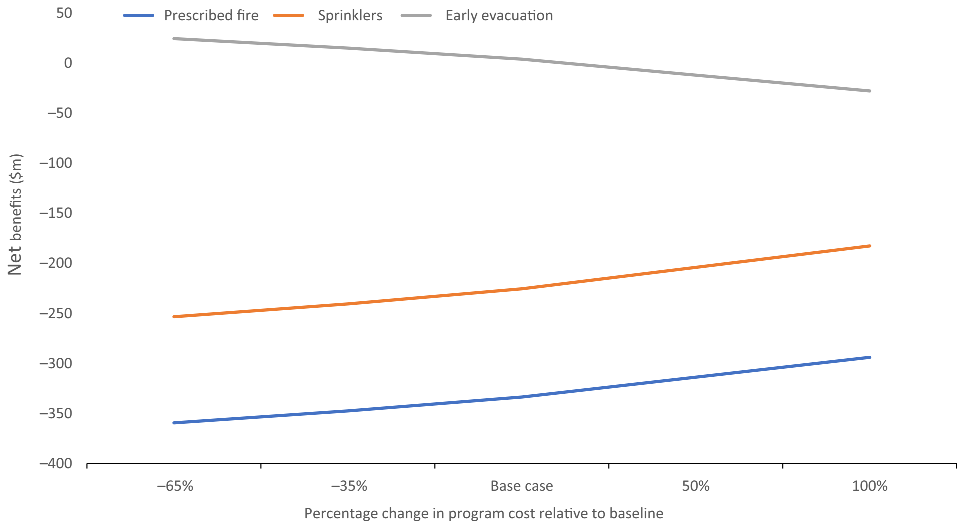

Figure 4 Sensitivity of expected annual net benefits of bushfire risk mitigation policies to program costs. [Colour figure can be viewed at wileyonlinelibrary.com]

et al. 2010). Overall, the risk of death among people who stayed with their homes was twice as high as the risk of death among people who evacuated late.

Even excluding the unusually severe Black Saturday bushfire event, more Australians have died when not evacuating themselves than when evacuating late. Australian bushfire policy appears to have encouraged people to stay with their homes although they did not have the capacity to defend them effectively (Parliament of Victoria 2010a), or adopt a ‘wait-and-see’ strategy, and evacuate late if threatened by the fire (Rhodes 2011). When fatality statistics are coupled with the finding in this paper that activities that increase the probability of successful home defence (home ignition zone treatments and additional prescribed fire) are economically inefficient, there is a strong argument against existing bushfire policy that encourages residents to stay and defend their homes.

We now turn to the practicality of an evacuation policy. The FFDI can be forecast spatially in advance, as it was during the week leading up to Black Saturday (Moncrief 2009). Daily reporting of fire danger ratings in television, radio and newspaper weather reports throughout the fire season may be useful to raise residents’ awareness about bushfire risk. Residents can be warned about extreme and catastrophic fire danger days in advance and encouraged to prepare to respond to a clear, unambiguous trigger to evacuate on such days. The trigger would be a bushfire ignition on an extreme or catastrophic FFDI day, coupled with expert opinion and state-of-the-art spatially explicit bushfire simulation models that identify communities threatened by the fire. The adoption of a compulsory evacuation policy raises issues of legality and civil liberties (we thank an anonymous referee for raising this point). These issues are discussed in Eburn (2014).

In summary, our analysis suggests that neither home ignition zone treatments nor an expansion of prescribed burning is likely to yield a cost-effective improvement on current policy. By contrast, a strong argument can be made for measures that facilitate early evacuation. These measures include support for development of household evacuation plans, warning systems to alert residents to act on their plan, and modifying activities of firefighters when fires are burning on high fire danger days to assist with evacuation, particularly of those unable to evacuate themselves.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1 Evidence of the effectiveness and cost of bushfire risk mitigation policies for southeast Australia.