Landscape and Urban Planning 174 (2018) 10–17

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

Options for reducing house-losses during wildfires without clearing trees and shrubs

Philip Gibbons[a,*], A. Malcolm Gill[a], Nicholas Shore[a], Max A. Moritz[b], Stephen Dovers[a], Geoffrey J. Cary[a]

[a] Fenner School of Environment and Society, The Australian National University, Canberra, ACT 2601, Australia
[b] University of California Cooperative Extension Division of Agriculture and Natural Resources & Bren School of Environmental Science & Management, Earth Research Institute, UC Santa Barbara, CA 93106, USA

GRAPHICAL ABSTRACT

Two houses impacted by a wildfire in southeastern Australia. Our study indicates that the “greenness”, spatial arrangement and proximity (relative to the wind direction) of trees and shrubs close to houses (within red circle) can be manipulated to reduce the risk of house losses during wildfires without necessarily clearing trees and shrubs. (Imagery supplied by South Australian Government.)

ARTICLE INFO

Keywords:
Bushfire
Wildfire
House loss
Fuel reduction
Hazard reduction
Wildland-urban interface

ABSTRACT

Removing vegetation close to houses is at the forefront of advice provided to home owners by fire management agencies. However, widespread clearing of trees and shrubs near houses impacts aesthetics, privacy, biodiversity, energy consumption and property values. Thus, stakeholders may oppose this practice. Regulators and property owners therefore require options for vegetation management that reduce risk to houses during wildfires without complete removal of trees and shrubs. Using data from 499 houses impacted by wildfires, we tested three hypotheses: (1) maintaining ‘green’ vegetation affords houses additional protection during wildfires; (2) risk posed by trees and shrubs near houses is reduced where they are arranged as many discrete patches; and (3) trees and shrubs retained in the upwind direction from which wildfires arrive represent greater risk to houses than trees and shrubs retained in the downwind direction. We found empirical support for each hypothesis. Increasing the mean Normalised Vegetation Difference Index (NDVI) (a measure of “greenness”) of vegetation near houses had the same effect on reducing house losses as removing some trees and shrubs. Trees and shrubs within 40 m of houses arranged as many discrete patches posed less risk than the same cover of trees and shrubs arranged as few discrete patches. Trees and shrubs retained downwind from houses represented less risk than

* Corresponding author at: Fenner School of Environment & Society, The Australian National University, Acton, ACT 2601, Australia.
E-mail addresses: philip.gibbons@anu.edu.au (P. Gibbons), nicholas.shore@anu.edu.au (N. Shore), mmoritz@ucsb.edu (M.A. Moritz), stephen.dovers@anu.edu.au (S. Dovers), geoffrey.cary@anu.edu.au (G.J. Cary).

https://doi.org/10.1016/j.landurbplan.2018.02.010
Received 8 June 2017; Received in revised form 15 February 2018; Accepted 20 February 2018
Available online 03 March 2018

trees and shrubs retained upwind. Our findings represent options for regulators or home owners seeking to balance risk posed by wildfires with benefits associated with retaining trees and shrubs near houses.

1. Introduction

House losses during wildfires are increasing in fire-prone regions of the world because of growing housing density at the wildland-urban interface (Crompton, McAneney, Chen, Pielke, & Haynes, 2010; Hughes & Mercer, 2009; McAneney, Chen, & Pitman, 2009). Houses are destroyed during wildfires when exposed to flame contact, radiant heat and/or burning embers. Because the likelihood or severity of flame contact, radiant heat and embers increase closer to burning vegetation (Cohen, 2000; Koo, Pagni, Weise, & Woycheese, 2010; Maranghides & Mell, 2011), it follows that the characteristics of vegetation close to houses is strongly associated with house loss during wildfires (Abt, Kelly, & Kuypers, 1987; Barrow, 1944; Gibbons et al., 2012; Ramsay, Macarthur, & Dowling, 1996; Syphard, Brennan, & Keeley, 2014; Wilson & Ferguson, 1986). Intensive management of vegetation (e.g., removal of trees and shrubs) close to houses is therefore at the forefront of advice provided to home owners by fire management agencies around the world (Gill & Stephens, 2009; Massada, Radeloff, & Stewart, 2011; Nelson, Monroe, & Johnson, 2005).

This advice results in widespread removal of trees and shrubs within, and adjacent to, the wildland-urban interface (Radeloff et al., 2005). The removal of this vegetation can have negative impacts on aesthetics and privacy (Nelson et al., 2005), biodiversity (Driscoll et al., 2010) and energy consumption (Bowler, Buyung-Ali, Knight, & Pullin, 2010); it can be associated with health effects (Tzoulas et al., 2007), influence property values (Pandit, Polyakov, Tapsuwan, & Moran, 2013) and be expensive for residents (Penman, Eriksen, Horsey, & Bradstock, 2016). Thus, there are different attitudes to vegetation clearing among stakeholders across the wildland-urban interface (Nelson et al., 2005). This limits the ability to achieve effective fuel reduction across those parts of the wildland-urban interface where there is considerable tree and shrub cover around houses, thereby placing some communities or individuals within them at increased risk from wildfire. Policy-makers and residents therefore require options for fuel management that can achieve a balance between the protection of houses from wildfire and the services provided by retaining trees and shrubs.

Our understanding of fire behaviour and the mechanisms that cause damage to houses during wildfires invite the following hypotheses:

(1) Maintaining 'green' vegetation affords houses additional protection during wildfires. Vegetation with a high moisture content requires more energy to ignite than cured vegetation. Fuel moisture plays an important role in the self-extinction of fires (Wilson & Ralph, 1985) and therefore fuel moisture influences the rate of spread of fires (Rothermel, 1972). Thus, maintaining "greener" landscaping is likely to result in a reduced probability of house loss during wildfires than drier gardens supporting equivalent cover of trees and shrubs.
(2) Risk posed by trees and shrubs near houses is reduced where they are arranged as many discrete patches. The propagation of fire depends on the properties of the flame and the properties of the fuel ahead of the flame (Catchpole, Hatton, & Catchpole, 1989) and so the spatial heterogeneity of fuels affect the rate at which fires spread (Burrows, Ward, & Robinson, 1991). This suggests that trees and shrubs arranged in a patchy distribution around houses will represent less hazard than an equivalent cover of trees and shrubs arranged in a more continuous distribution.
(3) Trees and shrubs in the upwind direction from which wildfires arrive represent greater risk to houses than trees and shrubs in the downwind direction. The effect of wind on the direction of flames, radiant heat and embers (Rothermel, 1972) suggests that trees and shrubs in the downwind direction from which wildfires arrive will have less effect on the likelihood of house loss than trees and shrubs close to houses in the upwind direction from which wildfires arrive.

We tested these hypotheses using data from three wildfires in south-eastern Australia.

2. Methods

2.1. Study area and sampling strategy

We sampled 499 houses from three wildfires that ignited on 7 February 2009 in south-eastern Australia (145°0′–146°50′E, 37°10′S–38°30′S). These wildfires, known as the East Kilmore, Murrindindi and Churchill fires, collectively burnt 194,403 ha and destroyed 1925 houses (Teague, McLeod, & Pascoe, 2010). The landscapes affected by these wildfires included rural areas where most native tree cover had been cleared, plantations dominated by introduced radiata pine (*Pinus radiata*), *Eucalyptus* forests managed for wood production and *Eucalyptus* forests managed as conservation estate. Housing occurred as a mix of rural, semi-rural and urban areas. Prior to sampling we stratified the study area by the three principal drivers of wildfire behaviour: weather, terrain and fuel (Countryman, 1972). Weather (measured using the Forest Fire Danger Index or FFDI) (McArthur, 1967), ranged from 5 to 189 (mean = 47.6). Slope ranged from 0.3° to 22.6° (mean = 8.5°). Fuel, measured as the % of land upwind from houses that had been burnt within ≤5 years and as the % of trees and shrubs cleared upwind from houses, ranged from 0% to 36% (mean = 2.8%) and 0% to 100% (mean = 32.3%) respectively. Houses were sampled using random points allocated in approximate proportion to the area of each stratum within a Geographical Information System (GIS). We sampled the nearest house to each random point using fine-scale (35 cm–50 cm pixel resolution) aerial imagery taken 1–37 months prior to the wildfires. We recorded damage to each sampled house as a binary variable (intact or destroyed) based on a visual inspection of fine scale (8–15 cm pixel resolution) aerial imagery in the visible spectrum taken 17–23 days after the wildfires. At each house we recorded a set of potential explanatory variables representing terrain; weather; and the amount, configuration, distance and direction to fuels from houses (Appendix A).

2.2. Statistical analysis

We used an information-theoretic approach (Burnham & Anderson, 1998) and Generalised Linear Modelling (GLM) to test our hypotheses. We commenced with a base model containing variables representing weather and fuel (measured at different scales) that are significantly ($p < 0.05$) associated with house loss during these wildfires as reported in a previous study (Gibbons et al., 2012). These variables were: weather (measured with FFDI), upwind distance to forest burnt within five years, the % cover of trees and shrubs and type of vegetation within 40 m of houses, total buildings within 40 m of houses, upwind distance to patches of trees and shrubs, upwind amount of private land and an 'autocovariate' to account for spatial autocorrelation between adjacent houses (Appendix A). We then compared this base model reported in Gibbons et al. (2012) with the following alternative models representing our hypotheses.

Hypothesis 1. Maintaining 'green' vegetation affords houses additional protection during wildfires.

To test this hypothesis we added to the base model a variable representing the average NDVI within 40 m from the centroid of each house. We measured NDVI to a distance of 40 m from each house because this is the maximum distance at which the three key mechanisms that destroy houses during wildfires—flame contact, radiant heat and embers—overlap and it is within this distance that the effects of vegetation on house loss are at their greatest (Gibbons et al., 2012; Syphard et al., 2014). Average NDVI was fitted as a polynomial term, as exploratory data analysis (using Generalised Additive Models) suggested there was a curvilinear relationship between the probability of house loss and average NDVI.

NDVI is strongly associated with active photosynthesis and water use in plants, distinguishes green vegetation from non-photosynthetic land classes (e.g., impervious surfaces and water) and has been used to predict the rate of irrigation in suburban gardens (Johnson & Belitz, 2012). We calculated NDVI in ArcMap using Landsat TM imagery sourced from the United States Geological Survey (USGS) Earth Explorer for the Kilmore-Murrundindi fire (dated 31 January 2009) and the Churchill fire (dated 24 January 2009). NDVI was calculated as

$$\frac{NIR-RED}{NIR+RED}$$

where *NIR* is the near infrared part of the electromagnetic spectrum that is reflected by leaves and *RED* is part of the electromagnetic spectrum that actively photosynthesising leaves absorb. NDVI values range from -1 (water) to $+1$ (green vegetation). Landsat TM multispectral imagery has a 30 m × 30 m spatial resolution. If half or more of the area of a pixel fell within 40 m of the centroid of each house then the value of that pixel was included in the calculation of average NDVI.

Hypothesis 2. Risk posed by trees and shrubs near houses is reduced where they are arranged as many discrete patches.

To test this hypothesis we added to the base model a variable representing the number of discrete patches of trees and shrubs within 40 m of each house, and a variable representing an interaction between the number of patches and % cover of trees and shrubs within 40 m of each house. We added the interaction term to test whether the arrangement of trees and shrubs within 40 m of houses as more discrete patches, compared with larger continuous patches, reduced the probability of house loss at all levels for tree and shrub cover within 40 m of houses. We counted patches of trees and shrubs manually around each of the 499 sampled houses using fine-scale (35 cm–50 cm pixel resolution) aerial imagery taken 1–37 months prior to the wildfires. A discrete patch of trees and shrubs was defined as visible tree and shrub canopies of any size that were at least 2 m from other trees and shrubs within 40 m from the centroid of each house.

Hypothesis 3. Trees and shrubs in the upwind direction from which wildfires arrive represent greater risk to houses than trees and shrubs in the downwind direction.

To test this hypothesis we added to the base model variables representing: the distance to the nearest large patch of trees and shrubs, the direction to that patch relative to the wind direction when the wildfire impacted each house and an interaction term between these variables. The distance from houses to the nearest large patch of trees and shrubs (>10 m width) and the direction from the house to the patch (degrees) were measured in ArcMap using fine-scale (35 cm–50 cm pixel resolution) aerial imagery taken 1–37 months prior to the wildfires. The direction to the nearest large patch of trees and shrubs was converted to one of eight cardinal or inter-cardinal directions and then compared with the wind direction recorded when wildfire impacted each house. The estimated time that wildfire impacted each house was estimated from fire progression maps (isochrones) for the Kilmore East and Murrindindi fires provided by the Victorian Department of Sustainability and Environment (now Department of Environment and Primary Industries) and for the Churchill fire provided by the Victorian Country Fire Authority; and wind direction to the nearest 30 min was taken from the nearest permanent automated weather station managed by the Bureau of Meteorology. Observed wind direction was converted to one of four inter-cardinal directions (i.e., north-east, south-east, south-west and north-west). The direction from each house to the nearest large patch of trees and shrubs relative to the wind direction when the wildfire impacted was recorded as: (i) upwind (0° difference); (ii) adjacent (45° to $<135°$ difference); and (iii) downwind ($\geq 135°$ difference). For example, where the direction of wind was recorded as NW at the time the wildfire reached a house of interest, vegetation patches in a NW direction from the house were classified 'upwind', patches in a N, W, NE or SW direction were classified 'adjacent', and all other patches (E, S and SE) were classified 'downwind.'

We included a further two alternative "global" models in the candidate set. The first included all of the variables representing each of the three hypotheses (the average NDVI of vegetation within 40 m of houses, the number of discrete patches of trees and shrubs within 40 m of houses, the distance to the nearest patch of trees and shrubs and the direction of that patch) to examine whether there was an additive effect of these variables. The second alternative model included each of these variables plus all of the interaction terms we tested.

Alternative models were judged to have strong empirical support where Akaike's Information Criterion (AIC) values were within ≤ 2 of the model with the lowest AIC value, were judged to have some

Table 1

Candidate models used to test our hypotheses, the variables included in those models, the log-likelihood of each model, AIC_c differences (ΔAIC_c) relative to the 'best' model and AIC_c weights for each model, which can be interpreted as the probability that the candidate model is the best of the set. Average NDVI was fitted as a polynomial term in all models in which it is included.

Model	Variables	Log-likelihood	ΔAIC_c	AIC_c weight
1	Base model	−252.621	3.53	0.07
2	Base model + average NDVI	−251.239	7.04	0.01
3	Base model + average NDVI + (average NDVI × % cover of trees and shrubs within 40 m)	−246.049	3.01	0.09
4	Base model + number of patches	−252.018	4.41	0.05
5	Base model + number of patches + (number of patches × % cover of trees and shrubs within 40 m)	−251.306	5.08	0.03
6	Base model + distance to nearest large patch of trees and shrubs + the direction of this large patch relative to the wind direction	−248.387	1.34	0.21
7	Base model + distance to nearest large patch of trees and shrubs + the direction of this large patch relative to the wind direction + (distance to nearest large patch of trees and shrubs × the direction of this large patch relative to the wind direction)	−247.251	3.29	0.08
8	Base model + average NDVI + number of patches + distance to nearest large patch of trees and shrubs + the direction of this large patch relative to the wind direction	−245.481	4.01	0.06
9	Base model + average NDVI + (average NDVI × % cover of trees and shrubs within 40 m) + (average NDVI × vegetation type) + number of patches + (number of patches × % cover of trees and shrubs within 40 m) + distance to nearest large patch of trees and shrubs + the direction of this large patch relative to the wind direction + (distance to nearest large patch of trees and shrubs × the direction of this large patch relative to the wind direction)	−236.976	0	0.41

empirical support where AIC differences were between > 2 and < 6 and were rejected where AIC differences were ≥6 (Symonds & Moussalli, 2011). We also calculated AIC weights for each model, which can be interpreted as the probability that the candidate model is the best of the set (Burnham & Anderson, 1998). All calculations of AIC were for small samples (AIC_c). All predictions from selected models were made with covariates held at their median (or for categorical variables the level with the highest sample size), except for FFDI, which was held at 100 (Catastrophic). Most houses destroyed during wildfires in Australia (64%) occurred on days when FFDI exceeded 100 (Blanchi, Lucas, Leonard, & Finkele, 2010) suggesting that it is at more severe weather conditions when the effect of these variables is most important. Errors around all means are 95% confidence limits. We also calculated Pearson correlation coefficients for all pairs of continuous variables. All statistical analyses were undertaken using R (R Development Core Team, 2010).

3. Results

The list of candidate models, the variables included in those models, AIC_c differences (ΔAIC_c) and AIC weights are provided in Table 1. The model with strongest empirical support was the global model that contained all terms representing our hypotheses plus the interaction terms (Model 9 in Table 1), suggesting an additive effect of each of the variables representing our hypotheses. The only model with no empirical support (i.e., $\Delta AIC_c > 6$) was Model 2 which was the base model with average NDVI added as a polynomial term.

3.1 Hypothesis 1: Maintaining 'green' vegetation affords houses additional protection during wildfires

Average NDVI values recorded within 40 m of houses ranged from 0.03 to 0.57 (median = 0.24) and the % cover of trees and shrubs within 40 m of houses ranged from 0% to 90% (median = 25%). Average NDVI was not highly correlated with the % cover of trees and shrubs within 40 m of houses (r = 0.41) so both of these variables were included in alternative models. There was some empirical support ($\Delta AIC_c = 3.01$) for the candidate model in which an interaction between average NDVI within 40 m of houses and the cover of trees and shrubs within 40 m of houses were added to the base model (Model 3 in Table 1). However, there was stronger empirical support for the full model that including this interaction and all of the other variables (Model 9 in Table 1). Predictions from this full model indicated that, for houses surrounded by a given percentage of trees and shrubs, the mean probability of house loss was less where vegetation surrounding the house had higher values for average NDVI, although there is considerable uncertainty around these predictions (Fig. 1). For example, if the cover of trees and shrubs around houses was 20% and the average NDVI was 0.20 then the mean probability of house loss is 0.53 ± 0.15. If the cover of trees and shrubs was doubled to 40% then the mean probability of house loss increases to 0.65 ± 0.15. However, if the NDVI can be concomitantly increased to 0.30, then the mean probability of house loss remains similar at 0.52 ± 0.15 despite doubling the cover of trees and shrubs.

3.2 Hypothesis 2: Risk posed by trees and shrubs near houses is reduced where they are arranged as many discrete patches

The number of discrete patches of trees and shrubs within 40 m of the sampled houses ranged from 0 to 46 (median = 10). The number of discrete patches of trees and shrubs within 40 m of houses was not highly correlated with the % cover of trees and shrubs within 40 m of houses (r = 0.33). Although there was some empirical support for the model including the number of patches of trees and shrubs within 40 m of houses (Model 4 in Table 1) and an interaction between this variable and the cover of trees and shrubs within 40 m of houses (Model 5 in Table 1), there was strongest empirical support for the full model that contained these terms plus all of the others examined here (Model 9 in

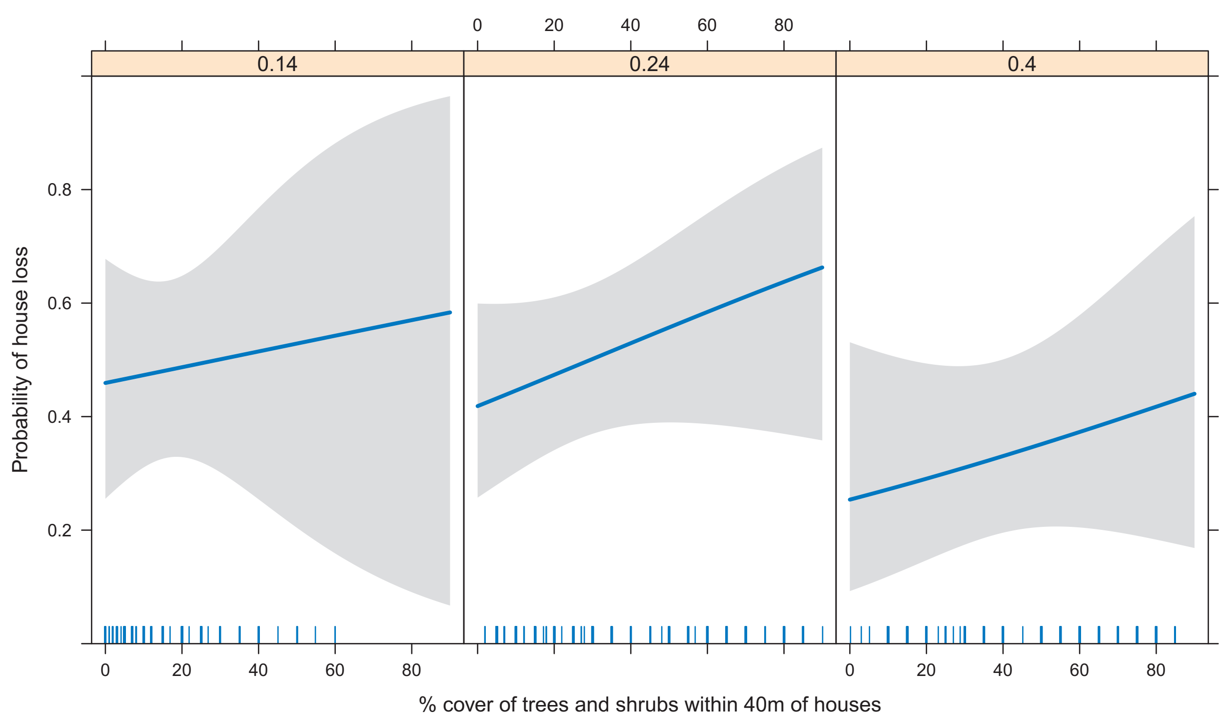

Fig. 1. The mean (± 95% confidence interval) predicted probability of house loss with changes to the % cover of trees and shrubs within 40 m of houses when the average NDVI of this vegetation is 0.14, 0.24 and 0.40 (i.e., the 10th, 50th and 90th percentiles). Predictions were made from Model 9 in Table 1 with all other continuous covariates held at their median except for FFDI which was fixed at 100.

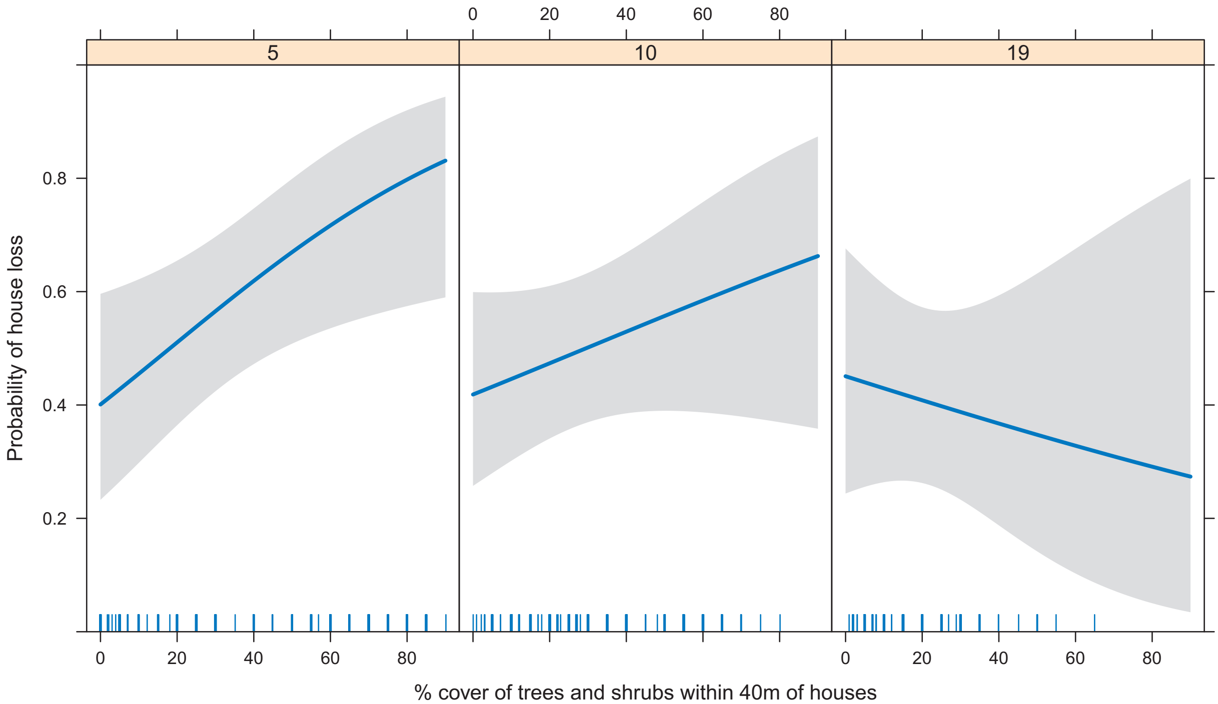

Fig. 2. The mean (± 95% confidence interval) predicted probability of house loss with changes to the total % cover of trees and shrubs within 40 m of houses when this vegetation was configured as 5, 10 or 19 discrete patches (i.e., the 10th, 50th and 90th percentiles). Predictions were made from Model 9 in Table 1 with all other continuous covariates held at their median except for FFDI which was fixed at 100.

Table 1). Predictions from this full model indicated that, other things being equal, the risk posed to houses from trees and shrubs within 40 m is reduced where that vegetation is configured as many discrete patches, particularly a higher levels of tree and shrub cover (Fig. 2). For example, houses surrounded by 50% cover of trees and shrubs configured as five discrete patches had a higher mean probability of house loss (0.67 ± 0.15) than houses surrounded by the same cover of trees and shrubs configured as 10 discrete patches (0.56 ± 0.17). However, predictions from this model should be disregarded at higher amounts of tree cover and a larger number of patches due to a high amount of uncertainty (i.e., wide confidence bands) (Fig. 2).

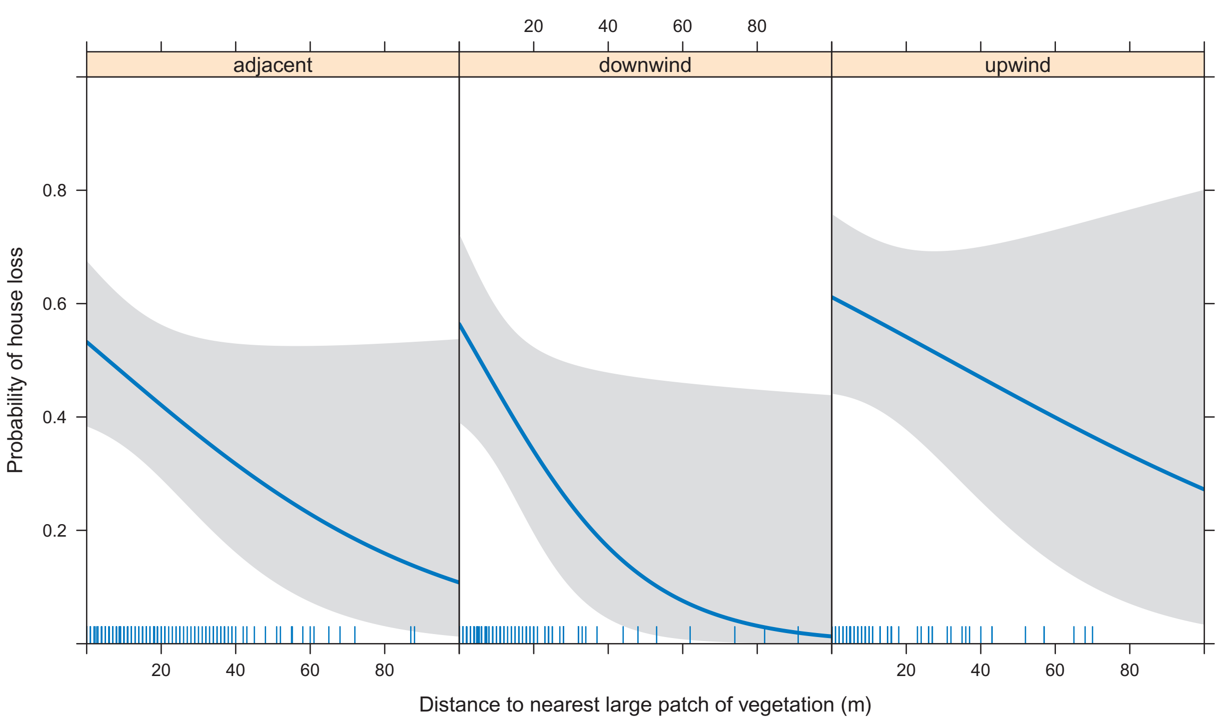

Fig. 3. The mean (± 95% confidence interval) predicted probability of house loss with distance to the nearest large patch of trees and shrubs (> 10 m across) when this patch is adjacent, downwind or upwind relative to wind direction when the wildfire impacted the house. Predictions were made from Model 9 in Table 1 with all other continuous covariates held at their median except for FFDI which was fixed at 100.

3.3 Hypothesis 3: Trees and shrubs in the upwind direction from which wildfires arrive represent greater risk to houses than trees and shrubs in the downwind direction

The distance from houses to the nearest large patch of trees and shrubs (> 10 m wide in its narrowest dimension) ranged from 0 to 433 m (median = 8 m). The % of the nearest large patches of vegetation that were upwind, adjacent and downwind from houses was 23%, 45% and 32% respectively. There was empirical support for models that included variables representing distance to the nearest large patch of trees and shrubs, the direction of large patches relative to the wind direction (Model 6 in Table 1) and/or an interaction term between these variables (Model 7 in Table 1). However, there was strongest support for the model that included these and all other terms (Model 9 in Table 1). Predictions from this latter model suggested that, for any given distance between houses and a large patch of trees and shrubs, there was a greatest risk to houses when this vegetation was upwind from houses, except when patches are very close to houses (Fig. 3). For example, other things being equal, predictions from this model indicated that the mean probability of house loss when the nearest large patch of trees and shrubs is located 10 m in the upwind direction was 0.58 ± 0.16, while this estimate was 0.45 ± 0.14 when the nearest large patch of trees and shrubs was 10 m in the downwind direction from houses.

4. Discussion

We sought to identify landscaping options that afford some protection to houses during wildfire, but represent an alternative to widespread removal of trees and shrubs, and thus provide options for home owners and regulators seeking to balance the protection of built assets and natural assets at the wildland-urban interface. Drawing on current understanding of wildfire behaviour and the mechanisms by which houses are destroyed during wildfires, we posed three hypotheses: (1) maintaining 'green' vegetation affords houses additional protection during wildfires; (2) risk posed by trees and shrubs near houses is reduced where they are arranged as many discrete patches; and (3) trees and shrubs in the upwind direction from which wildfires arrive represent greater risk to houses than trees and shrubs in the downwind direction. We found evidence to support each our hypotheses.

4.1. Maintaining 'green' vegetation affords houses additional protection during wildfires

For any amount of tree and shrub cover within 40 m of houses, there were slightly lower predicted house losses where this area had higher average values for NDVI. NDVI is positively associated with the density of vegetation, vegetation "greeness" (the degree to which vegetation is photosynthesising) and the moisture content of vegetation (Ceccato, Flasse, Tarantola, Jacquemoud, & Grégoire, 2001; Gamon et al., 1995). Further, NDVI is indicative of reflectance in the upper vegetation stratum at a site rather than vegetation in lower strata. Thus, it is not clear which of the variables correlated with NDVI is critical with respect to house loss. However, given average NDVI within 40 m of houses was only weakly positively correlated with the % cover of trees and shrubs within 40 m of houses and NDVI had an additional effect to the % cover of trees and shrubs around houses (Table 1), our results suggest that 'greenness' of the upper stratum of vegetation is a factor associated with house loss during wildfire. Some plants have naturally higher moisture content and this is, in turn, associated with lower flammability (Gill & Moore, 1996). Thus, the negative association between average NDVI and house loss may indicate that the selection of plants with lower flammability affords houses some protection during wildfire—a strategy recommended in some wildfire-prone areas (Detweiler & Fitzgerald, 2006). The level of irrigation used in gardens is also positively associated with NDVI (Johnson & Belitz, 2012) and therefore our results could also suggest that irrigating vegetation around houses could reduce risk to houses as an alternative, or adjunct to, removing trees and shrubs. However, this strategy is likely only to be effective where there is capacity to increase "greeness" among the plant species around houses, which may not be feasible among plant species adapted to relatively low available water, which is the case for many native plant species in our study area. Therefore, advantages from irrigation may only be realised with the concomitant replacement of some plant species with others. However, notwithstanding any of these issues, there was considerable scope to substantially increase the average NDVI of vegetation around houses: 34% of houses were surrounded by vegetation with an average NDVI ≤ 50% of the 90th percentile (0.40).

4.2. Risk posed by trees and shrubs near houses is reduced where they are arranged as many discrete patches

Trees and shrubs within 40 m of houses arranged as many discrete patches posed less risk to houses than the same cover of trees and shrubs arranged as few discrete patches—particularly at higher levels of cover for trees and shrubs (Fig. 2). As fuels become less continuous, the heat transfer between burning fuel and adjacent fuel becomes less efficient and the intensity and spread of a fire will decline (Rothermel, 1972). Effects of fuel patchiness on fire behaviour have been confirmed in the field by several authors (e.g., Bradstock & Gill, 1993; Burrows et al., 1991). On the other hand, a wider spacing between trees and shrubs can result in less sheltering of wind during fire (Zylstra et al., 2016), although we are unaware of any empirical studies where this has been linked to reduced house losses. The effect of patchiness among trees and shrubs on house loss during wildfires is likely to have greatest effect where fuel between patches of trees and shrubs (e.g., grass) is insufficient to maintain the intensity or rate of spread of the fire. However, benefits from increasing the number of patches of trees and shrubs became increasingly uncertain where the total number of patches and the cover of trees and shrubs were close to maximum observed values (Fig. 2), possibly reflecting few observations in the field where a high cover of trees and shrubs could be configured as many discrete patches.

4.3 Trees and shrubs in the upwind direction from which wildfires arrive represents a greater risk to houses than trees and shrubs in the downwind direction

Our results indicated that patches of trees and shrubs represented greatest risk when they occurred in the upwind direction from which the wildfire arrived, except where this vegetation was very close to houses (Fig. 3). Fire is more likely to propagate rapidly downwind because fuels are exposed to relatively greater convective and radiant heat (Rothermel, 1972), and direct ignition by flames. Further, embers are a key factor in the ignition of houses during wildfires (Barrow et al., 1944; Chen & McAneney, 2004; Cohen, 2000) and will predominantly travel downwind from a fire. However, fuels downwind or adjacent to houses during a wildfire can represent a hazard where they are close enough to direct radiant heat to the structure, where convective winds caused by the fire are drawn towards the structure from multiple directions, or on lee slopes where fires can spread laterally relative to wind direction (Sharples, McRae, & Wilkes, 2012). This may explain why fuels adjacent to, or downwind, from the prevailing wind direction still pose a risk to houses, albeit a relatively lower risk than fuels upwind from houses. Our results therefore suggested that, on average, less intensive fuel management downwind from houses can be tolerated without increasing the probability of house loss. However, this is only a useful strategy where the directions from which wildfires arrive at houses are consistent.

4.4. Implications for policy

In wildfire-prone regions management agencies may permit, or demand, home-owners to remove some vegetation near houses. These regulations are often generic. For example, in two of the most wildfire-prone states of Australia, regulations focus on the removal of trees and shrubs to set distances from houses (New South Wales Rural Fire Service, 2015; Victorian Department of Planning & Community Development, 2011). However, trees and shrubs provide many services such as aesthetics, privacy, shade and biodiversity (Driscoll et al., 2010; Nelson et al., 2005) and many people are attracted to the wildland-urban interface because of these (Nelson et al., 2005). Thus, individuals may be reluctant to clear vegetation around their houses (Nelson et al., 2005) placing some of the community at greater risk than others. Our results suggest that reducing the risk that trees and shrubs pose to houses during wildfires can be achieved without necessarily removing all trees and shrubs. Each of the three strategies examined here—-maintaining a green garden, retaining vegetation in discrete clumps and retaining more vegetation downwind from houses (with less vegetation retained upwind)—are options for fuel management that reduce risk to houses during wildfires without blanket removal of trees and shrubs and thus may be more acceptable fuel management options to some stakeholders. Accommodating diverse interests at the wildland-urban interface is likely to result in more uniform hazard reduction than imposing blanket approaches that are not supported by all stakeholders.

However, it is important to note that the management of vegetation close to houses alone will not eliminate risks to houses and occupants from wildfire. Other variables not considered in this study such as building design and the ability to actively defend a house can also affect house losses during wildfire (Penman et al., 2013). Further, the efficacy of strategies such as vegetation management decline with the severity of fire weather conditions (Gibbons et al., 2012). Thus, other strategies such as evacuation well before wildfires impact houses combined with adequate house insurance, building codes that reduce risk of house loss during wildfires and planning controls that limit house construction in areas with high risk must always be considered alongside vegetation management when managing risks to communities from wildfires.

5. Conclusions

We identified three landscaping options around houses—increasing the ‘greenness’ of vegetation, configuring trees and shrubs as many discrete patches, and focusing tree and shrub removal in the upwind direction from houses—that individually or together reduce the risk of house loss during wildfires without requiring the total removal of trees and shrubs. These findings represent options for regulators or home owners seeking to balance risk posed by wildfires with benefits associated with retaining trees and shrubs at the wildland-urban interface (e.g., privacy, aesthetics, biodiversity, shade). We encourage policy-makers to consider our findings as information that can be made available to residents and other actors at the wildland-urban interface to use in light of their individual circumstances rather than imposing uniform standards or regulations.

Acknowledgements

We would like to thank several officers in the Victorian Government for providing data that was used in this study. Dr Wade Blanchard provided statistical advice. This research was supported by the Australian Government through the Australian Research Council's *Discovery Projects* funding scheme (project DP150100878). The views expressed herein are those of the authors and are not necessarily those of the Australian Government or Australian Research Council. Three anonymous referees provided constructive comments on earlier versions of this manuscript.

Appendix A

Explanatory variables included in the base model used to predict house loss.

Variable	Definition
Buildings	The number of buildings (excluding circular water tanks) visible on the imagery intersecting a circle with a radius of 40 m from the centroid of each house
% cover of trees and shrubs	Visual estimate of % woody vegetation within a circle with a radius of 40 m from the centroid of each house using the pre-fire imagery. This estimate was verified against digitised data
Vegetation type (planted and remnant)	A visual assessment of whether woody vegetation within a circle with a radius of 40 m from the centroid of each house was predominantly planted or remnant using the pre-fire imagery. The features of trees and shrubs that were indicative of their origin were: crown texture, size, shape and arrangement relative to trees in nearby remnant vegetation
Distance upwind to nearest of trees or shrubs	Distance from each house to nearest group of ≥ 2 trees or shrubs (or one tree if its canopy was ≥ 10 m wide) from the edge of the house in the upwind direction measured manually in a GIS using the pre-fire imagery
Distance upwind to nearest block of trees	Distance from each house to nearest block of trees ≥ 50 m wide at the narrowest point from the edge of the house in the upwind direction measured manually in a GIS using the pre-fire imagery
Distance upwind to mapped cleared land	Distance from each house to nearest area without woody vegetation as mapped in the NV2005_EXTENT GIS raster provided by the then Victorian Department of Sustainability and Environment (DSE) in the upwind direction
% cleared upwind	% mapped woody vegetation calculated along a transect in the upwind direction from each house to the 2009 wildfire boundary using the NV2005_EXTENT GIS raster provided by DSE
Amount of land not burnt for ≤ 5 years upwind	Amount (m) of land from each house that was not burnt for ≤ 5 years prior to 2009 (as mapped in the PROD_FIRE_LASTBURNT100 layer provided by DSE) measured in the upwind direction
Upwind amount of private land	Amount (m) of land from each house that is not a public land tenure (as mapped in the PLM100 GIS shape file provided by DSE) in the upwind direction
Forest Fire Danger Index (FFDI)	Calculated using the formula $FFDI = 2.0 \times \exp(-0.450 + 0.987\ln(DF) - 0.0345RH + 0.338T + 0.0234V)$ where, DF is drought factor, RH is relative humidity (%), T is air temperature (°C) and V is wind speed (km h^{-1}). Weather variables used to calculate FFDI were derived from half-hourly data recorded at the closest weather station to each house

References

Abt, R., Kelly, D., & Kuypers, M. (1987). The Florida Palm Coast fire: An analysis of fire incidence and residence characteristics. *Fire Technology, 23*, 186–197.

Barrow, G. J. (1944). A survey of houses destroyed by the Beaumaris fire, January 14 1944. *Journal of the Council for Scientific and Industrial Research, 18*.

Blanchi, R., Lucas, C., Leonard, J., & Finkele, K. (2010). Meteorological conditions and wildfire-related house loss in Australia. *International Journal of Wildland Fire, 19*, 914–926.

Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning, 97*(3), 147–155.

Bradstock, R., & Gill, A. (1993). Fire in semiarid, mallee shrublands-size of flames from discrete fuel arrays and their role in the spread of fire. *International Journal of Wildland Fire, 3*(1), 3–12.

Burnham, K. P., & Anderson, D. R. (1998). *Model selection and inference: A practical information-theoretic approach.* New York: Springer-Verlag.

Burrows, N., Ward, B., & Robinson, A. (1991). Fire behaviour in spinifex fuels on the Gibson Desert nature reserve, Western Australia. *Journal of Arid Environments, 20*(2), 189–204.

Catchpole, E., Hatton, T., & Catchpole, W. (1989). Fire spread through nonhomogeneous fuel modelled as a Markov process. *Ecological Modelling, 48*(1), 101–112.

Ceccato, P., Flasse, S., Tarantola, S., Jacquemoud, S., & Grégoire, J.-M. (2001). Detecting vegetation leaf water content using reflectance in the optical domain. *Remote Sensing of Environment, 77*(1), 22–33.

Chen, K., & McAneney, J. (2004). Quantifying bushfire penetration into urban areas in Australia. *Geophysical Research Letters, 31*, L12212.

Cohen, J. D. (2000). Preventing disaster: Home ignitability in the wildland-urban interface. *Journal of Forestry, 98*, 15–21.

Countryman, C. M. (1972). *The fire environment concept.* Boise, Idaho: National Wildfire Coordinating Group.

Crompton, R. P., McAneney, K. J., Chen, K., Pielke, R. A., & Haynes, K. (2010). Influence of location, population, and climate on building damage and fatalities due to Australian Bushfire: 1925–2009. *Weather, Climate, and Society, 2*(4), 300–310.

Detweiler, A. J., & Fitzgerald, S. A. (2006). *Fire-resistant plants for home landscapes: Selecting plants that may reduce your risk from wildfire, [Covallis, Or.].* Oregon State University Extension Service.

Driscoll, D. A., Lindenmayer, D. B., Bennett, A. F., Bode, M., Bradstock, R. A., Cary, G. J., et al. (2010). Resolving conflicts in fire management using decision theory: Asset-protection versus biodiversity conservation. *Conservation Letters, 3*(4), 215–223.

Gamon, J. A., Field, C. B., Goulden, M. L., Griffin, K. L., Hartley, A. E., Joel, G., et al. (1995). Relationships between NDVI, canopy structure, and photosynthesis in three Californian vegetation types. *Ecological Applications, 5*(1), 28–41.

Gibbons, P., van Bommel, L., Gill, A. M., Cary, G. J., Driscoll, D. A., Bradstock, R. A., et al. (2012). Land management practices associated with house loss in wildfires. *PLoS One, 7*(1), e29212.

Gill, A. M., & Moore, P. H. (1996). *Ignitibility of leaves of Australian plants. A contract report to the Australian Flora Foundation.* Canberra: CSIRO Plant Industry.

Gill, A. M., & Stephens, S. L. (2009). Scientific and social challenges for the management of fire-prone wildland–urban interfaces. *Environmental Research Letters, 4*(3), 034014.

Hughes, R., & Mercer, D. (2009). Planning to reduce risk: The wildfire management overlay in Victoria, Australia. *Geographical Research, 47*(2), 124–141.

Johnson, T. D., & Belitz, K. (2012). A remote sensing approach for estimating the location and rate of urban irrigation in semi-arid climates. *Journal of Hydrology, 414*, 86–98.

Koo, E., Pagni, P. J., Weise, D. R., & Woycheese, J. P. (2010). Firebrands and spotting ignition in large-scale fires. *International Journal of Wildland Fire, 19*(7), 818–843.

Maranghides, A., & Mell, W. E. (2011). A case study of a community affected by the Witch and Guejito wildland fires. *Fire Technology, 47*, 379–420.

Massada, A. B., Radeloff, V. C., & Stewart, S. I. (2011). Allocating fuel breaks to optimally protect structures in the wildland–urban interface. *International Journal of Wildland Fire, 20*(1), 59–68.

McAneney, J., Chen, K. P., & Pitman, A. (2009). 100-years of Australian bushfire property losses: Is the risk significant and is it increasing? *Journal of Environmental Management, 90*(8), 2819–2822.

McArthur, A. G. (1967). *Fire behaviour in eucalypt forest.* Canberra: Commonwealth of Australia Forestry and Timber Bureau.

Nelson, K. C., Monroe, M. C., & Johnson, J. F. (2005). The look of the land: homeowner landscape management and wildfire preparedness in Minnesota and Florida. *Society and Natural Resources, 18*(4), 321–336.

New South Wales Rural Fire Service (2015). *10/50 vegetation clearing code of practice for New South Wales.* Sydney: NSW Rural Fire Service.

Pandit, R., Polyakov, M., Tapsuwan, S., & Moran, T. (2013). The effect of street trees on property value in Perth, Western Australia. *Landscape and Urban Planning, 110*, 134–142.

Penman, T., Eriksen, C., Blanchi, R., Chladil, M., Gill, A. M., Haynes, K., et al. (2013). Defining adequate means of residents to prepare property for protection from wildfire. *International Journal of Disaster Risk Reduction, 6*, 67–77.

Penman, T. D., Eriksen, C., Horsey, B., & Bradstock, R. A. (2016). How much does it cost residents to prepare their property for wildfire? *International Journal of Disaster Risk Reduction, 16*, 88–98.

R Development Core Team (2010). *R: A language and environment for statistical computing.* Vienna, Austria: R Foundation for Statistical Computing.

Radeloff, V. C., Hammer, R. B., Stewart, S. I., Fried, J. S., Holcomb, S. S., & McKeefry, J. F. (2005). The wildland–urban interface in the United States. *Ecological Applications, 15*(3), 799–805.

Ramsay, G. C., Macarthur, N. A., & Dowling, V. P. (1996). Building in a fire-prone environment: Research on building survival in two major bushfires. *Proceedings of the Linnean Society of New South Wales, 116*, 133–140.

Rothermel, R. C. (1972). *A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service Research Paper INT-115*.

Sharples, J. J., McRae, R. H., & Wilkes, S. R. (2012). Wind–terrain effects on the propagation of wildfires in rugged terrain: Fire channelling. *International Journal of Wildland Fire, 21*(3), 282–296.

Symonds, M. R., & Moussalli, A. (2011). A brief guide to model selection, multimodel inference and model averaging in behavioural ecology using Akaike's information criterion. *Behavioral Ecology and Sociobiology, 65*(1), 13–21.

Syphard, A., Brennan, T., & Keeley, J. (2014). The role of defensible space for residential structure protection during wildfires. *International Journal of Wildland Fire, 23*(8), 1165–1175.

Teague, B., McLeod, R., & Pascoe, S. (2010). *2009 Victorian bushfires royal commission.* Final reportMelbourne: Parliament of Victoria.

Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kaźmierczak, A., Niemela, J., et al. (2007). Promoting ecosystem and human health in urban areas using green infrastructure: A literature review. *Landscape and Urban Planning, 81*(3), 167–178.

Victorian Department of Planning and Community Development (2011). *Amendment VC83 – bushfire protection. Vegetation exemptions. Advisory note 39.* Melbourne: Victorian Department of Planning and Community Development.

Wilson, A. A. G., & Ferguson, I. S. (1986). Predicting the probability of house survival during bushfires. *Journal of Environmental Management, 23*(3), 259–270.

Wilson, J. R., & Ralph, A. (1985). Observations of extinction and marginal burning states in free burning porous fuel beds. *Combustion Science and Technology, 44*(3–4), 179–193.

Zylstra, P., Bradstock, R. A., Bedward, M., Penman, T. D., Doherty, M. D., Weber, R. O., et al. (2016). Biophysical mechanistic modelling quantifies the effects of plant traits on fire severity: Species, not surface fuel loads, determine flame dimensions in eucalypt forests. *PLoS One, 11*(8), e0160715.