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The effectiveness of prescribed burning for protecting houses during wildfires in Australia

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Abstract

Background Approximately 14,000 houses have been destroyed during wildfires in Australia since 1900, and the number of houses lost per decade continues to rise. Greater application of prescribed burning is one strategy employed to mitigate this trend, but there is debate about its effectiveness. We sampled 1617 houses that were exposed to wildfire in southern Australia and explored associations between the proportion of these houses that were destroyed and the per cent of the landscape previously burnt (by prescribed burning or wildfire).

Results After controlling for other variables that affected house loss (i.e. weather, terrain and woody vegetation near houses), the proportion of houses destroyed during wildfire decreased with the per cent of the landscape previously burnt in the upwind direction, but only where previous burning occurred within 5 years and < 3 km upwind from houses. However, we found the majority of sampled houses (69%) had no prescribed burning within 5 years and < 3 km upwind. The amount of woody vegetation within 40 m of houses had a stronger and more certain negative association with house losses than previous burning.

Conclusions Our findings suggest prescribed burning: (a) is generally conducted too far from houses to reduce losses, unless it effectively halts wildfires before they reach houses; (b) could play a greater role in mitigating house losses during wildfires, but only if substantially more burning can be done within 3 km from houses; and (c) is less effective than removing woody vegetation immediately adjacent to houses (i.e. establishing defensible space). Overall, we found limited evidence that prescribed burning, as currently practised in Southern Australia, reduces house losses during wildfires.

Keywords Wildfire, Bushfire, Prescribed burning, Hazard-reduction, Houses, Australia

Resumen

Antecedentes Alrededor de 14.000 casas han sido destruidas por incendios de vegetación en Australia desde el 1900, y este número de pérdidas de casas continúa creciendo. Una mayor aplicación de las quemaduras prescritas es una estrategia empleada para mitigar esta tendencia, aunque se debate sobre su efectividad. Muestreamos 1.617 casas que estuvieron expuestas a incendios de vegetación en el sur de Australia y exploramos la asociación entre la proporción de las casas que fueron destruidas y el porcentaje del paisaje circundante que había sido previamente quemado (tanto por quemaduras prescritas o incendios anteriores).

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Resultados Luego de controlar otras variables que afectaron la pérdida de casas (i. e. clima, terreno, y vegetación leñosa cerca de las casas), la proporción de casas destruidas durante incendios de vegetación decrecieron con el porcentaje de del paisaje previamente tratado en la dirección del viento (a barlovento), aunque solo donde quemas previas ocurrieron dentro de los 5 años y < 3 km de casas ubicadas a barlovento del incendio. Sin embargo, encontramos que la mayoría de las casas muestreadas (69%) no habían tenido quemas prescritas dentro de los 5 años previos y ubicadas < 3 km a barlovento. La cantidad de vegetación leñosa dentro de los 40 m de las casas tuvo una asociación negativa más fuerte con las pérdidas de casas que las que habían sido tratadas previamente con quemas prescritas.

Conclusiones Nuestros resultados sugieren que las quemas prescritas: (a) son conducidas generalmente muy lejos de las casas como para reducir pérdidas, al menos de que estas quemas efectivamente reduzcan los incendios antes de que este llegue a las casas; (b) pueden jugar un rol mayor en mitigar las pérdidas de casas durante incendios de vegetación, pero sólo si quemas sustanciales son realizadas dentro de los de 3 km alrededor de las casas; y (c) son menos efectivas que la remoción directa de la vegetación adyacente a las casas. En general, encontramos evidencia limitada que las quemas prescritas, tal como son llevadas a cabo actualmente en el sur de Australia, reduzcan la pérdida de casas durante incendios de vegetación.

Background

Approximately 14,000 houses have been destroyed during wildfires in Australia since 1900 (data from Haworth et al. 2015; Blanche et al. 2012; Binskin et al. 2020; Rich et al. 2016). Houses are an important asset to protect during wildfires because their loss has a considerable financial impact (Wang et al. 2021), the loss of houses dislocates communities (McWethy et al. 2019) and, most importantly, many people killed during wildfires are sheltering in, or defending, their home (Blanche et al. 2012, 2014). Despite advances in fire science and fire-fighting techniques, the number of houses destroyed per decade during wildfires in Australia continues to rise (Fig. 1). This trend is attributed to factors including population growth in peri-urban areas (Radeloff et al. 2018), climate change (Abram et al. 2021) and increasing fire fuel loads (Clarke et al. 2016).

Prescribed burning is often recommended as a strategy to reduce fuel loads and thus mitigate the loss of houses during subsequent wildfires (Teague et al. 2010; AFAC 2016; Morgan et al. 2020; Fernandes and Botelho 2003). Although prescribed burning is also undertaken for other legitimate reasons (i.e., to protect fire-sensitive habitat, to improve habitat for some species, to promote regeneration after timber harvesting, to control introduced plants, to reduce carbon emissions and for cultural reasons by First Nations peoples), a key objective of prescribed burning in southern Australia (AFAC 2016) and other fire-prone regions (Schoennagel et al. 2009) is to protect property such as houses. It is with respect to this objective that we evaluated prescribed burning in this study.

Prescribed burning can reduce the severity of subsequent wildfires and thus can help land managers suppress them (Fernandes 2015). In their inquiry into the 2019–20 wildfires in New South Wales, Australia, which resulted in the loss of 2,476 houses, Owens and O’Kane (2020)

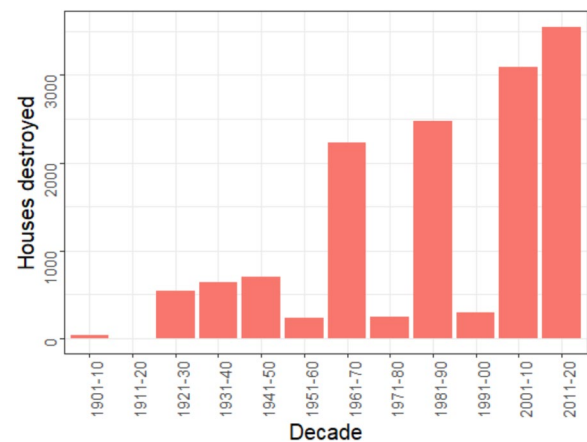


Fig. 1 House losses during wildfires in Australia by decade between 1901 and 2020 (data from Haworth et al. 2015; Blanche et al. 2012; Binskin et al. 2020; Rich et al. 2016)

documented examples where prescribed burning enabled wildfires to be controlled before reaching the urban interface, but concluded that prescribed burning could not be relied upon to stop the majority of wildfires from impacting houses. This conclusion is supported by an earlier study in the Sydney region of Australia, where Price and Bradstock (2010) found there was a 10% chance a wildfire would intercept and then stop in an area that had been prescribe-burnt in the previous 5 years. Similarly, of 2,657 km of wildfire boundary examined in south-eastern Australia, approximately 13% occurred in or adjacent to areas that had burnt in the previous 10 years (Tolhurst and McCarthy 2016). As with Price and Bradstock (2010), Tolhurst and McCarthy (2016) found that wildfires were less likely to stop in previously burnt areas as the severity of the weather increased. These results are consistent with observations that the ability of prescribed burns to

modify wildfire behaviour diminishes with increasing severity of the weather (Tolhurst and McCarthy 2016; Fernandes and Botelho 2003; Price and Bradstock 2012; Collins et al. 2023; Gale et al. 2023), which are the conditions when most house-losses in Australia occur (Blanchi et al. 2010).

Where prescribed burning does not stop wildfires before reaching houses, it can potentially mitigate the hazard from wildfires by modifying wildfire behaviour. Prescribed burning can reduce the rate of spread of subsequent wildfires (McCaw et al. 2012; Fernandes 2015) so a strategic value of prescribed burning might occur if the rate of spread of wildfires is slowed sufficiently to provide residents and firefighters greater time to prepare or mobilise resources before houses are impacted (Owens and O'Kane 2020). Prescribed burning can also reduce hazard from airborne embers (Fernandes 2015), which is the key mechanism that causes house losses during wildfires in Australia (Ramsay et al. 1996; Leonard and Bowditch 2003; Barrow 1944). The propagation of embers from wildfires in southern Australia is reduced where there has been previous burning within 3–10 years (Fernandes and Botelho 2003; Tolhurst and McCarthy 2016; Gould et al. 2007; Price and Bradstock 2012; McCaw et al. 2012; Collins et al. 2023). Although embers represent an indirect hazard to houses because they can cause spotting many kilometres downwind from a wildfire (Storey et al. 2020), research in Australia suggests embers represent a direct hazard to houses up to 0.4–2 km downwind from a wildfire front (Tolhurst and Howlett 2003; Ellis 2011; Wang 2006). This is supported by observational (Penman et al. 2014; Gibbons et al. 2012) and simulation (Penman et al. 2020) studies that have found that prescribed burning is more effective if undertaken closer to houses.

In summary, although prescribed burning does not appear to stop the majority of wildfires, there is some evidence it can reduce the hazard to houses associated with wildfires by modifying fire behaviour. Thus, there have been calls to increase the amount of prescribed burning in southern Australia (Teague et al. 2010; AFAC 2016; Morgan et al. 2020). However, there is ongoing debate about the effectiveness of prescribed burning in the weather conditions typically associated with house losses, and about where in the landscape prescribed burning is most effective for reducing house losses: should we invest in prescribed burning to reduce house losses and, if so, should we expand the area of the broader landscape treated with prescribed burns, or concentrate these efforts near houses? To address these questions, we examined associations between house losses during wildfires and the percentage of the landscape treated with prescribed burns at varying distances upwind from houses.

Methods

Study area

We randomly sampled houses in 13 wildfire events that occurred in southern Australia between 2009 and 2020 (Table 1, Fig. S1). Only wildfires with known house losses were sampled. The climate across the study area is temperate based on the Köppen climate classification (Stern et al. 2000), but can be further divided into areas with a distinctly dry season (and warm to hot summer) in south-west Western Australia and South Australia; and no distinct dry season (warm to mild summer) in New South Wales, Victoria and Tasmania (Stern et al. 2000). However, the study area was characterised by periods of severe drought caused by the El Niño–Southern Oscillation (Philander 1983) or the Indian Ocean Dipole (Saji et al. 1999) and these periods of extended drought are when most house losses from wildfires occur (Blanchi et al. 2010).

The predicted pre-European vegetation types at sampled houses (Department of Climate Change 2024) were predominantly eucalypt open forests (56% of houses), eucalypt woodlands (34% of houses), shrublands (5% of houses) and eucalypt tall open forests (2% of houses). Tall eucalypt open forests may have return fire intervals of > 100 years, eucalypt open forests and woodlands typically have return fire intervals of 20–100 years, and low open forests and shrublands may have fire intervals as short as 5–20 years (Murphy et al. 2013). However, fire intervals have been decreasing for the last four decades across much of the study area (Canadell et al. 2021).

The dominant land use upwind from sampled houses was conservation and natural environments (59% of houses), production from relatively natural environments (16% of houses), production from dryland agriculture and plantations (13% of houses) and other land uses (12% of houses). All houses sampled in this study were detached dwellings in rural, semi-rural or urban settings with a range of construction materials, but dominated by brick cladding and steel or tile roofing. Structures such as mobile homes and caravans, which can be particularly vulnerable to wildfire (Troy et al. 2022), garages or sheds were not sampled unless they formed part of a larger detached dwelling.

Measured variables

We randomly sampled houses that fell within the mapped boundary of each wildfire using aerial imagery taken prior to each wildfire. Houses were sampled without knowing if the house was later destroyed during the wildfire. We recorded damage sustained to each sampled house as a binary variable (not destroyed/destroyed) from aerial imagery taken within two years after each wildfire. We recorded a house as destroyed if at least part

Table 1 Wildfire events in which houses were sampled in this study

Date	State	Fire name	Houses sampled
7 February 2009	Victoria	Churchill	55
7 February 2009	Victoria	Kilmore East/Murrundindi	444
10 January 2011	Western Australia	Lake Clifton	56
6 February 2011	Western Australia	Roleystone	113
23 November 2011	Western Australia	Margaret River	130
4 January 2013	Tasmania	Forcett	109
13 October 2013	New South Wales	Wambelong	83
17 October 2013	New South Wales	Springwood	158
17 October 2013	New South Wales	State Mine	53
12 January 2014	Western Australia	Parkerville	126
3 January 2015	South Australia	Sampson Flat	129
8–26 November 2019	New South Wales	North Coast complex	61
31 Nov 2019–5 Jan 2020	New South Wales	South Coast complex	100
Total			1617

of the roof had visibly collapsed or the house had been demolished. All imagery was orthorectified, had a spatial resolution of 15 to 124 cm and was sourced from Google Earth (Maxar Technologies, CNES/Airbus, Sinclair Knight Merz, DigitalGlobe, AEROMetrex & Jacobs), the Victorian Government or DigitalGlobe.

We recorded several covariates at each sampled house reflecting the key variables that affect fire behaviour (i.e. weather, terrain and fuel) (Pyne et al. 1996) (Table 2). We recorded weather at the approximate time each house was impacted by wildfire (measured as the Forest Fire Danger Index (FFDI)) as weather is an important variable affecting fire behaviour and house loss during wildfires (Tolhurst and McCarthy 2016; McCaw et al. 2012). An interaction between slope and aspect was included to control for the effects of terrain on fire behaviour (Cheney et al. 2012). Spatial data for actual fuel loads were not available across our study area when each wildfire occurred, so we characterised fuel using a number of different covariates. The loss of houses in Australian wildfires is positively associated with the cover of proximal woody vegetation (Price et al. 2021; Gibbons et al. 2012; Ramsay et al. 1996; Wilson and Ferguson 1986). We measured this as the cover of trees and shrubs within 40 m of houses, which is the maximum distance that radiant heat is likely to ignite a wooden structure and is considered to create a zone of defensible space (Cohen 2000). We also recorded the per cent of woody vegetation in compass quarters with radii of ≤ 100 m, ≤ 500 m and ≤ 1000 m centred on the upwind direction from each house at the estimated time the house was impacted by wildfire and the dominant land use upwind from houses. We measured the nearest mapped vegetation formation upwind from each house given vegetation type, or more

specifically the types of plants present, has a considerable influence on wildfire behaviour (Zylstra et al. 2016). Adjacent structures to each house are another potential source of fuel. We measured the distance from each house to the nearest detached structure from the aerial imagery taken prior to each wildfire to test whether this contributed to house loss as house-to-house transmission has been identified as a potential risk factor in southern Australia (Price et al. 2021) and has been established in other countries (Troy et al. 2022).

The extent of, and time since, the last fire were key variables in our analyses. We combined the area of prescribed burns and wildfires within each sector in Fig. 2 because these were highly correlated within each sector ($r \geq 0.84$). We only included prescribed burns and wildfires that occurred across the study area in the previous 10 years given the effect of previous burning on fire behaviour typically does not persist beyond this (Bradstock et al. 2010; Boer et al. 2009; Gibbons et al. 2012; Fernandes and Botelho 2003; Collins et al. 2023), although we acknowledge some studies have found the effect of prescribed burning can diminish before 5 years (Fernandes and Botelho 2003; Dixon et al. 2018).

Data analysis

We explored associations between the probability of house loss and the measured variables in Table 2 using Generalised Linear Mixed Models (GLMMs) with a binomial distribution given house loss was recorded as a binary variable (0,1). Before models were fitted, we removed all highly correlated fixed effects based on the Pearson correlation coefficient. All fixed effects were standardised by subtracting the mean from the observed value and dividing by the standard deviation before

Table 2 Explanatory variables measured at each sampled house

Variable	Definition
% of landscape previously burnt upwind	Measured as the per cent of the land upwind from each house that intersected prescribed fires or wildfires in the previous 5 years or previous 10 years at distances of 0–2 km, 2–3 km, 3–4 km, 4–5 km and 5–10 km as illustrated in Fig. 2. The locations of prescribed fires and wildfires were sourced as shapefiles from open data sources managed by state government agencies (i.e., https://data.sa.gov.au/ , https://www.seed.nsw.gov.au/ , https://listdata.thelist.tas.gov.au/opendata/ , https://www.data.vic.gov.au/ , https://www.data.wa.gov.au/). The upwind direction was the wind direction recorded in the nearest Australian Government Bureau of Meteorology weather station at the approximate time that each house was impacted by wildfire
Forest Fire Danger Index (FFDI)	FFDI was calculated using the formula (Noble et al. 1980): $FFDI = 2 \times \exp(0.4500 + 0.9870 \ln(DF) - 0.0345RH + 0.3380T + 0.0234V)$, where, DF is drought factor which incorporates the accumulated soil moisture deficit (Dowdy 2018), RH is relative humidity (%), T is air temperature ($^{\circ}\text{C}$) and V is wind speed (km hr^{-1}). Weather variables used to calculate FFDI were taken from the closest Bureau of Meteorology weather station to each house at the approximate time of wildfire impact, which was estimated from fire progression maps, post-fire inquiries or media reports
Slope (degrees)	Derived from a 1 s (approximately 30 m) digital elevation model and calculated as the mean within a circular neighbourhood with a radius of 100 m around each house
Aspect (–1 to 1)	Aspect relative to north where north = 1, east or west = 0 and south = –1 calculated as $\cos(\text{aspect})$ where aspect (in radians) is averaged within a circular neighbourhood with a radius of 100 m around each house from a 1 s (approximately 30 m $\times$ 30 m) digital elevation model
% cover of woody vegetation (within 40 m radius)	Visually estimated from imagery with a 15 cm to 124 cm pixel resolution captured prior to each wildfire within a circle with radius of 40 m originating at the approximate centroid of each house. This value represents the per cent of the plot occupied by canopy cover rather than projective foliage cover
% cover of woody vegetation (upwind)	The per cent cover of woody vegetation upwind from each house was measured within a wedge or compass quarter of 90 degrees centred on the upwind direction from each house with radii of 100 m, 500 m and 1000 m. Woody vegetation was as mapped in National forest and Sparse Woody Vegetation Data (Version 3 2018 Release) which is derived using a time-series of Landsat images at a 25 m grid resolution
Dominant land use (upwind)	The dominant mapped land use ((1) conservation and natural environments, (2) production from relatively natural environments, (3) dryland agriculture and plantations, and (4) other) in a sector with a 90-degree angle and 5 km radius centred on the upwind direction from which the wildfire arrived at each house
Distance to nearest structure (m)	The latitude and longitude of the edge of the nearest detached structure to each house (excluding circular water tanks) was recorded and the distance between the centroid of the sampled house and this structure estimated using the Haversine formula (Robusto 1957)
Nearest vegetation formation (upwind)	The nearest mapped vegetation formation in the upwind direction from which the wildfire arrived at each house classified as follows: (1) native closed forest (80–100% crown cover); (2) native open forest (50–80% crown cover); (3) native woodland (20–50% crown cover); (4) non-forest (0–20% crown cover); (5) unknown forest ($\geq 20\%$ crown cover); (6) other

model fitting. All parameters were estimated using maximum likelihood because we compared models with different fixed effects. Given multiple houses were sampled from within 13 fire events, some occurring in the same geographical region and each subject to similar weather conditions and similar suppression strategies, it is possible there is some degree of autocorrelation between these houses. To address this, we fitted fire event as a random effect in each candidate model and tested for spatial autocorrelation between residuals in the selected models using Moran's I .

We used multi-model inference (Burnham and Anderson 2002) to rank candidate models. We did this in two steps to avoid fitting too many models. The first set of candidate models (Table S1) was compared to identify

the top-ranked model for predicting house loss using variables that capture the effects of weather, terrain and fuel, ignoring previous fire upwind from houses (hereafter the “base model”). We then added to this base model variables representing the per cent of the landscape burnt at different distances upwind from houses (i.e., 0–2 km, 2–3 km, 3–4 km, 4–5 km and 5–10 km) in the previous 5 years and the previous 10 years (Table S2).

Candidate GLMMs were ranked by Akaike's Information Criterion adjusted for small samples (AICc). We report p -values for variables in the selected models as information only, as Burnham and Anderson (p. 84) (2002) warn against conflating model selection using AIC with tests of significance. The probability each model was the best in the candidate set was evaluated using Akaike

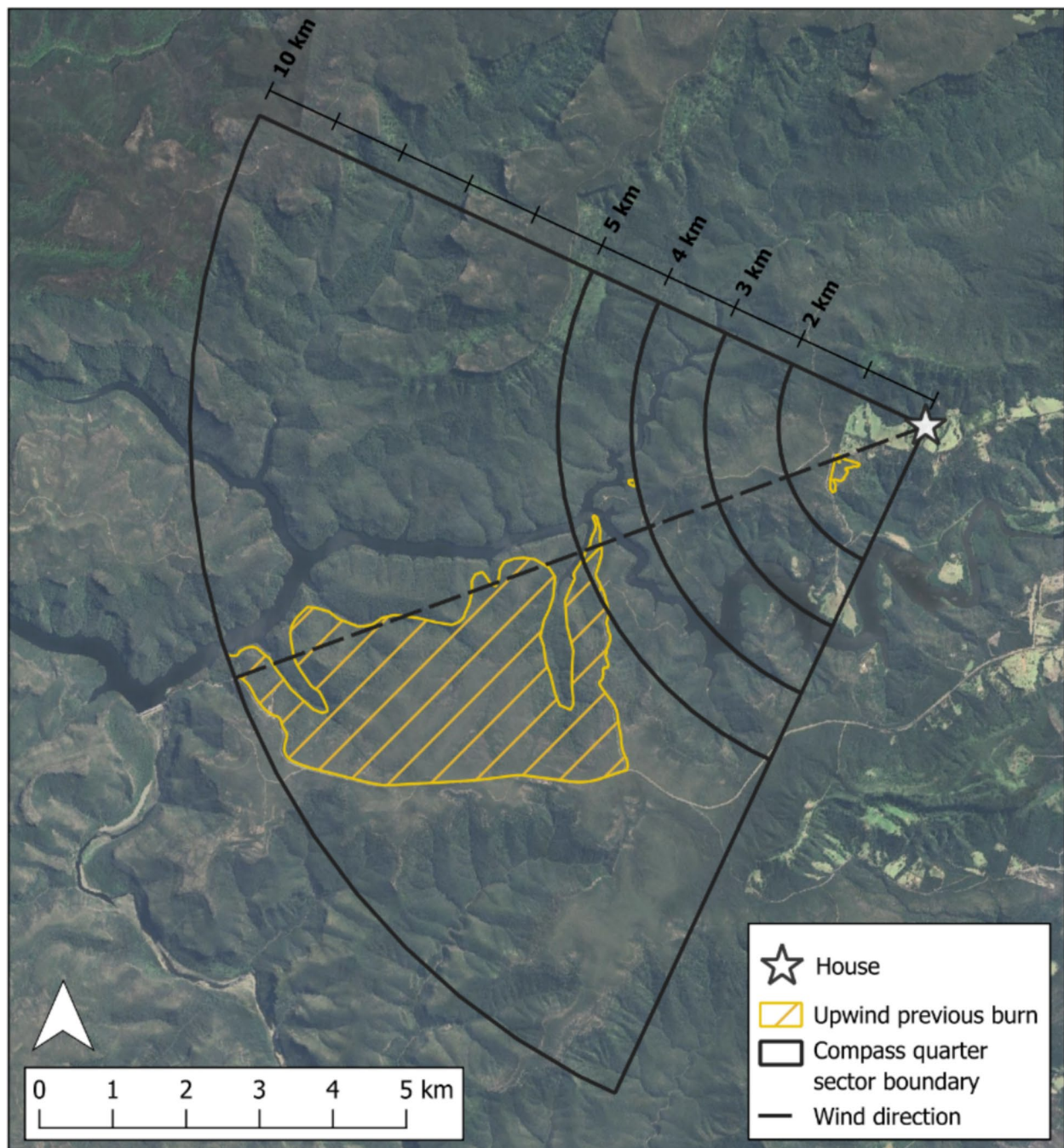


Fig. 2 We calculated the per cent of the landscape that was previously burnt at different distances upwind from each house. Prescribed burns or wildfires in the previous 5 years or previous 10 years (yellow) were intersected with sectors that were 0–2 km, 2–3 km, 3–4 km, 4–5 km and 5–10 km in the upwind direction (dashed line) recorded at the nearest weather station when wildfire impacted each house

weights ($wAIC$) and the ability of selected models to predict the proportion of houses destroyed was evaluated using the area under the receiver operating characteristic curve (AUC), which is the rate at which the model predicts true positives relative to false positives. The values of AUC range from 0.5 (no better than random)

to 1.0 (perfect discrimination), with values of 0.7–0.8 considered acceptable and >0.9 excellent discrimination (Mandrekar 2010). The relative importance of fixed effects in each model (i.e. effect sizes) was evaluated using log-odds. Residuals for each GLMM were tested for normality, homoscedasticity and the occurrence of

outliers. Variance Inflation Factors were calculated for fixed effects in each model as a post hoc test for correlation between explanatory variables.

Analyses were undertaken using the following packages in R (R Development Core Team 2010): variables were standardised using “scale()” in the base version (R Development Core Team 2010); GLMMs were fitted using GLM-Mtmb (Magnusson et al. 2017); multi-model inference was undertaken using MuMIn (Barton 2009); Variance Inflation Factors were calculated using Performance (Fox et al. 2012; Lüdecke et al. 2021); the pattern of the residuals for each GLMM and Moran's I was calculated using DHARMA (Hartig and Hartig 2017); AUC was calculated using pROC (Robin et al. 2021); predictions from selected models were calculated using ggpredict (Lüdecke et al. 2020); and charts were created using ggplot2 (Wickham 2011).

Results

Summary statistics

We sampled 1617 houses across 13 wildfires. A total of 481 (30%) of the sampled houses were destroyed

by wildfire. Summary statistics for the measured variables are reported in Table 3. Houses exposed to wildfire typically occurred adjacent to relatively intact forest or woodland. Natural forested environments (i.e., conservation or production) were the dominant upwind land use for 75% of sampled houses, and the mean per cent cover of woody vegetation within 100 m, 500 m and 1000 m upwind from houses was 68%, 72% and 75%, respectively. Most sampled houses (81%) had some previous fire (prescribed burning or wildfire) recorded within 10 km upwind in the previous 5 years. The per cent of sampled houses with prescribed burning upwind in the previous 5 years at distances of 0–2 km, 0–3 km, 0–4 km, 0–5 km and 0–10 km was 19%, 31%, 48%, 59% and 74%, respectively; and the per cent of houses with prescribed burning upwind in the previous 10 years at the same distances was 24%, 37%, 54%, 64% and 78%.

Some measured variables were highly correlated and thus removed before model fitting. The per cent of the landscape previously burnt upwind from houses by prescribed burning was highly correlated ($r \geq 0.84$) with the

Table 3 Minimum, maximum and mean values for each of the covariates recorded at sampled houses

Variable	Minimum	Maximum	Mean
Forest Fire Danger Index (FFDI)	1	189	42
Slope (degrees)	0	22	6.2
Nearest structure (m)	0	4469	336
% cover of woody vegetation (within 40 m radius)	0	100	34
% cover of woody vegetation (within 100 m upwind)	0	100	68
% cover of woody vegetation (within 500 m upwind)	0	100	72
% cover of woody vegetation (within 1000 m upwind)	0	100	75
% burnt upwind within 5 years (prescribed fire) (0–2 km)	0	46	1.4
% burnt upwind within 5 years (prescribed fire and wildfire) (0–2 km)	0	47	2
% burnt upwind within 5 years (prescribed fire) (2–3 km)	0	58	1.9
% burnt upwind within 5 years (prescribed fire and wildfire) (2–3 km)	0	69	2.4
% burnt upwind within 5 years (prescribed fire) (3–4 km)	0	62	2.4
% burnt upwind within 5 years (prescribed fire and wildfire) (3–4 km)	0	73	3.1
% burnt upwind within 5 years (prescribed fire) (4–5 km)	0	56	4.2
% burnt upwind within 5 years (prescribed fire and wildfire) (4–5 km)	0	65	4.7
% burnt upwind within 5 years (prescribed fire) (5–10 km)	0	43	6
% burnt upwind within 5 years (prescribed fire and wildfire) (5–10 km)	0	43	7.4
% burnt upwind within 10 years (prescribed fire) (0–2 km)	0	64	2
% burnt upwind within 10 years (prescribed fire and wildfire) (0–2 km)	0	89	3.2
% burnt upwind within 10 years (prescribed fire) (2–3 km)	0	63	2.4
% burnt upwind within 10 years (prescribed fire and wildfire) (2–3 km)	0	69	3.7
% burnt upwind within 10 years (prescribed fire) (3–4 km)	0	65	3.7
% burnt upwind within 10 years (prescribed fire and wildfire) (3–4 km)	0	73	4.7
% burnt upwind within 10 years (prescribed fire) (4–5 km)	0	59	5.8
% burnt upwind within 10 years (prescribed fire and wildfire) (4–5 km)	0	65	6.8
% burnt upwind within 10 years (prescribed fire) (5–10 km)	0	43	8.2
% burnt upwind within 10 years (prescribed fire and wildfire) (5–10 km)	0	56	11

per cent of the landscape previously burnt by prescribed burning and wildfire in the same time-frame (i.e., within 5 years or within 10 years) and distance upwind from houses (0–2 km, 2–3 km, 3–4 km, 4–5 km or 5–10 km) and thus the total amount of previous burning (i.e., prescribed burning and wildfire) was used in all models. The per cent of the landscape previously burnt 3–4 km upwind from houses by prescribed burning or wildfire was moderately highly correlated with the per cent previously burnt 4–5 km upwind from houses ($r=0.71$). However, both variables were retained and a post-hoc test of correlation (i.e., Variance Inflation Factors) was used to confirm if the variables were highly correlated after fitting models. The per cent cover of woody vegetation within 500 m from houses was highly correlated with the per cent cover of woody vegetation within 1000 m from houses ($r=0.90$) so the former was removed from subsequent analyses.

A base model for predicting house loss

We first identified a base model for predicting house loss that did not contain variables reflecting previous burning upwind from houses. The highest-ranked model (lowest AICc) from the candidate set of models in Table S1 was Model 4, which contained the following variables: FFDI, slope $\times$ northness and per cent woody vegetation within a 40 m radius. The probability this was the best model in the set of models tested in Table S1 was 0.181 based on $wAIC$. This model had an AUC value of 0.77, indicating the model had an acceptable level of discrimination between true positives and false positives. Variance Inflation Factors in this model were ≤ 1.08 , indicating low correlation between fixed effects. A Moran's I test indicated the residuals did not vary significantly from a random spatial distribution ($p=0.7683$) suggesting no distance-based autocorrelation. Predictions from this model indicated that the proportion of houses destroyed during wildfire increased with, in order of effect size, the cover of woody vegetation within a 40 m radius of houses, FFDI and steeper slopes on northerly aspects (Fig. 3, Table S3, Fig. S2). The closest competing model in the candidate set ($wAIC=0.177$) was Model 5, which contained the same fixed effects as Model 4 and the cover of woody vegetation within 100 m upwind from houses.

The effect of previous burning on house loss

Adding variables representing previous burning at different distances upwind from houses improved the base model reported above (i.e., reduced the AICc). Of the candidate models that included previous burning upwind from houses (Table S2), the top-ranked model was Model 19, which, in addition to the fixed effects in the base model, contained in order of effect size the per

cent of the landscape burnt upwind from houses in the previous 5 years at distances of 2–3 km, 3–4 km and 0–2 km (Table 4, Table S4, Fig. S3). The probability this was the best model of those in Table S2 was 0.144. This model had an AUC value of 0.78. Variance Inflation Factors for this model were ≤ 1.77 indicating low correlation between fixed effects. A Moran's I test indicated the residuals did not vary significantly from a random spatial distribution ($p=0.7631$) suggesting no distance-based autocorrelation. The effect size for the per cent cover of woody vegetation was three times that of prior burning 2–3 km upwind from houses and had less uncertainty (Fig. S3). Although several other models had support (i.e., $\Delta AICc \leq 2$) (Table 4), predictions from these models all indicated negative associations between house losses and previous burning only where the latter occurred < 3 km upwind (Fig. S4).

Predictions from the top-ranked model in Table 4 indicated that, after controlling for the effects of FFDI, slope, aspect and cover of woody vegetation within 40 m, the mean proportion of houses destroyed decreased with the amount of burning 2–3 km upwind from houses (Fig. 4, Fig. S3). House losses also reduced with the amount of burning 0–2 km upwind, but this relationship had higher uncertainty, in part because there was a relatively low number of houses for which there was prior burning within 2 km. House losses, on average, were predicted to increase with the amount of burning 3–4 km upwind, but this relationship was also uncertain as indicated by wide confidence intervals. With FFDI fixed at 75 (extreme) and all other variables held at their mean, the predicted mean ($\pm 95\%$ confidence interval) proportion of houses destroyed was 0.30 (0.19, 0.44). With no prior burning upwind from houses, the predicted proportion of houses destroyed was virtually unchanged at 0.32 (0.21, 0.47). When woody vegetation within 40 m of houses was reduced to the minimum observed (0%), the predicted proportion of houses destroyed was reduced to 0.10 (0.05, 0.17). Under the same initial conditions, 30% of the landscape within 3 km from houses would need to be burnt every 5 years to reduce the predicted proportion of houses destroyed to 0.10 (0.03, 0.26).

Discussion

There have been calls to increase the area of prescribed burning after major house-loss wildfires in Australia (Teague et al. 2010; AFAC 2016; Morgan et al. 2020). Our results indicated that, after controlling for other measured variables that affected house loss (i.e., woody vegetation near houses, FFDI, terrain), the proportion of houses destroyed during wildfire decreased with the per cent of the landscape burnt by prescribed burning or

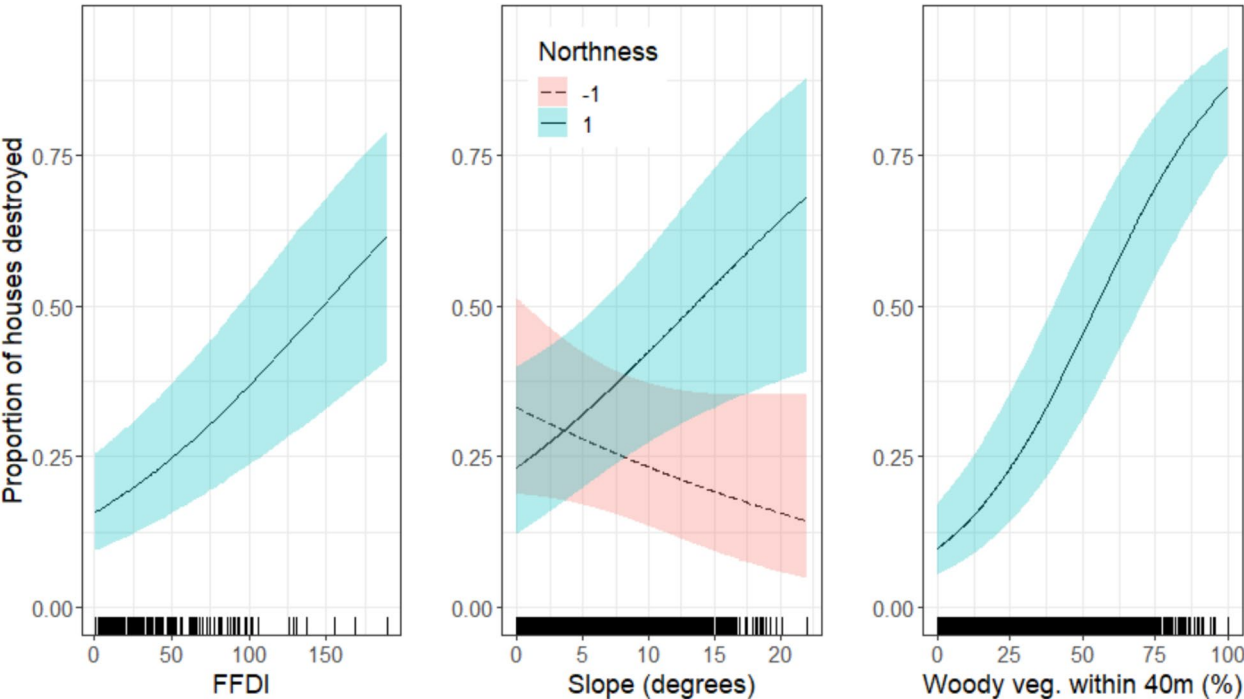


Fig. 3 The predicted mean ($\pm$ 95% confidence interval) proportion of houses destroyed with changes to each of the variables in the base model (i.e. excluding any previous burning upwind from houses). Predictions are based on Model 4 in Table S1. Predictions for slope are provided for houses with north (1) and south (–1) aspects. Predictions for each fixed effect are calculated while holding the other fixed effects at their mean, except for FFDI which was fixed at 75 to simulate “extreme” fire weather. Dashes above the x-axes indicate values for sampled houses

Table 4 Generalised linear mixed models from those fitted in Table 4 that had empirical support ($\Delta\text{AICc} \leq 2$), their AICc differences (ΔAICc) and probability the model is the best of all models tested (wAIC). Models are ranked from those with most to least support. The “+” signs indicate variables added to each model

Model	Random effect	Fixed effects							ΔAICc	wAIC	
		Fire event	Variables in base model	Years	% burnt upwind						
					0–2 km	2–3 km	3–4 km	4–5 km			5–10 km
19	+	+	0–5	+	+	+			0	0.144	
22	+	+	0–5		+	+	+	+	0.20	0.131	
18	+	+	0–5	+	+				0.48	0.114	
31	+	+	0–10		+	+	+	+	1.58	0.065	
34	+	+	0–10					+	1.71	0.061	
21	+	+	0–5	+	+	+	+	+	1.91	0.055	
20	+	+	0–5	+	+	+	+		1.96	0.054	

wildfire, but only where prior burning occurred < 3 km upwind from houses and in the previous 5 years. However, we found most (69%) houses had no prescribed burning within 3 km and that current patterns of burning had little effect on reducing house losses during subsequent wildfires. Reducing woody vegetation within 40 m of houses had a stronger and more certain effect on reducing house losses than prior burning.

Why is prescribed burning more effective closer to houses
We suggest there are three key explanations for our results:

- (1) Wildfires are more likely to intercept previous burning conducted closer to houses.

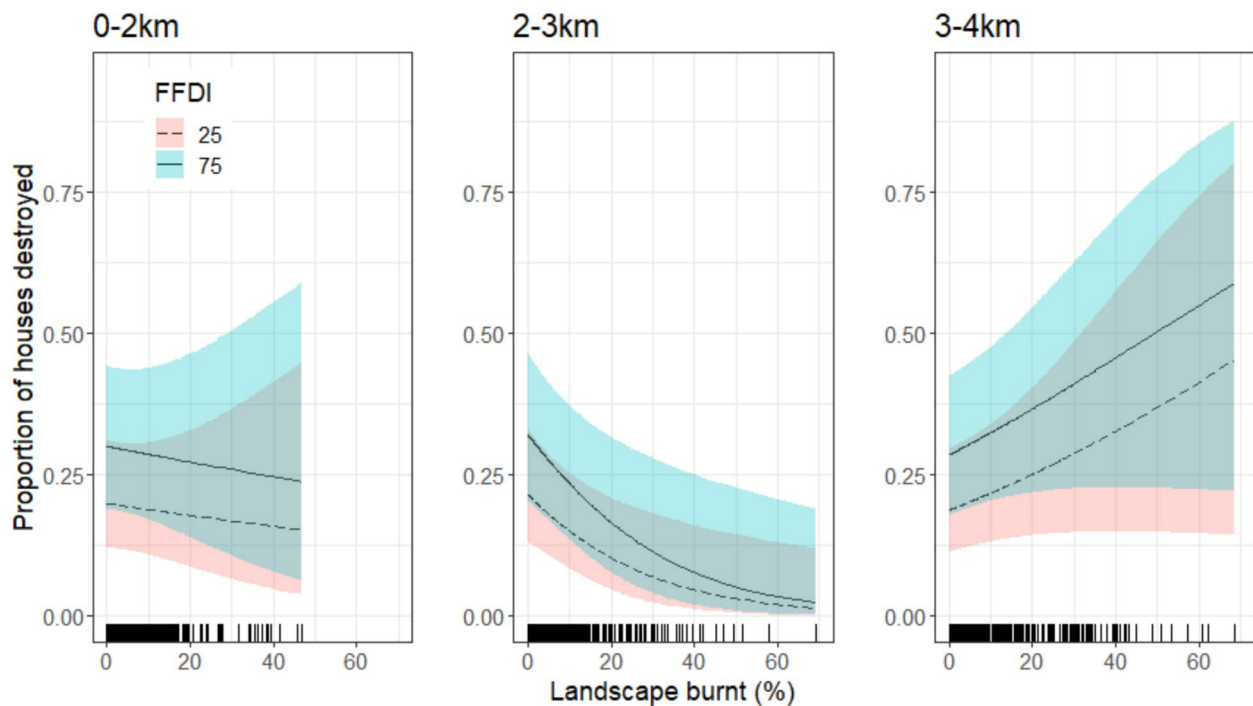


Fig. 4 The predicted mean ($\pm 95\%$ confidence interval) proportion of houses destroyed with per cent of the landscape burnt in the previous 5 years at distances of 0–2 km, 2–3 km and 3–4 km upwind from houses while controlling for other variables in the base model that are associated with house loss. Predictions for burning upwind within 5 years are based on the top-ranked model (Model 19 in Table 4). All predictions are calculated while holding the other fixed effects in the same model at their mean, and FFDI at 25 (very high) and 75 (extreme). Dashes above the x-axes indicate values for sampled houses

Price and Bradstock (2010) concluded that prescribed burning closer to assets such as houses was preferable because it increases the likelihood that wildfires encounter—and thus are influenced by—prescribed burns before reaching houses. In this study, an average of 1.4–6% of the landscape at different distances upwind from houses was treated with prescribed burning within 5 years and thus, even if wildfires come from a consistent direction such as a single compass quarter, there is only a small probability a wildfire front will intercept, either partially or fully, a previous burn. In the Sydney region of southern Australia, Price and Bradstock (2010) found 22% of wildfires intersected a prescribed burn from the previous 5 years and 10% of wildfires intercepted and stopped within a prescribed burn. That is, most wildfires are able to move around, through or over prescribed burns. The closer a prescribed burn is undertaken to an asset such as a house, the smaller the area that must be treated to ensure that any subsequent wildfire intercepts a previously burnt area before reaching adjacent houses. Prescribed burning undertaken further from houses must be larger to have the same effect.

- (2) Prescribed burning close to houses reduces embers. Most house losses during Australian wildfires are associated with impact from airborne embers (Ramsay et al. 1996; Leonard and Bowditch 2003; Barrow 1944). Prescribed burning reduces the propagation of embers in subsequent wildfires (McCaw et al. 2012). Although embers can lead to spotting which, in turn, increases the rate of spread of a wildfire, embers typically represent a direct hazard to houses up to 0.4–2 km downwind from a fire front (Tolhurst and Howlett 2003; Ellis 2011; Wang 2006). This is consistent with our result that prescribed burning is negatively associated with house losses only when undertaken within 3 km upwind from houses.
- (3) The rural and urban interface provides conditions that complement the effects of prescribed burning. The urban or rural interface is often characterised by modified fuel structure or fire breaks, roads, a reliable water supply and good access. These may complement the effect of prescribed burning. For example, reducing fire fuel within 20–40 m of houses creates a zone of defensible space (Gibbons et al. 2012; Price et al. 2021; Syphard et al. 2014). That

we found additive effects between prescribed burning and the amount of clearing within 40 m from houses supports this conclusion. Further, Price and Bradstock (2010) found that wildfires were more likely to stop at a previous burn where it was co-located with a road. Perimeter roads are often used at the rural–urban interface to increase the distance between woody vegetation and houses (Bond and Mercer 2014). Prescribed burning undertaken further from the rural or urban interface is unlikely to have these same co-benefits.

Limitations of prescribed burning close to houses

Although our results indicated that prescribed burning or previous wildfire is likely to have greatest benefit for protecting houses if conducted within 5 years and upwind within 3 km, only 31% of sampled houses had prescribed burning within this distance and timeframe, and the average amount of previous burning (from prescribed fire and wildfire) was too small to reduce house losses. There are several factors that limit the amount of prescribed burning that can be undertaken close to houses: prescribed burning close to houses may expose a large number of people to smoke (Jaffe et al. 2020), will often involve burning on privately owned land (Schoenagel et al. 2009), can represent a considerable hazard if it escapes from control lines (Ryan et al. 2013) and thus may be suitable in a narrower range of circumstances and weather conditions than prescribed burning further from houses. The added risks and number of stakeholders affected by prescribed burning close to houses also demand greater planning and resources, and thus cost (Berry and Hessel 2004). For this reason, Florec et al. (2019) concluded it was more cost-effective to burn larger areas farther from houses. However, Penman et al. (2020) concluded the opposite on the basis they predicted that prescribed burning farther from houses had little effect on reducing the risk of house loss—a conclusion supported by our study.

Our results indicated that prescribed burning—even if conducted close to houses—was less certain and not as strongly associated with house losses as reducing the cover of trees and shrubs within 40 m from houses. Prescribed burning may not be as effective as clearing vegetation because it only partially and temporarily reduces some components of fuel hazard (McCaw et al. 2012; Collins et al. 2023). For example, Collins et al. (2023) found considerable residual fuel hazard within the boundary of prescribed burns. Compared with prescribed burning, clearing vegetation can substantially reduce or eliminate surface, near-surface and elevated fuels. Clearing can also

be undertaken closer to houses than prescribed burning and thus reduce radiant heat and flame contact in addition to embers—all of which contribute to house losses (Cohen 2000; Syphard et al. 2014). At the closest distance from houses that prescribed burning is generally feasible, it is only likely to influence ember density.

Our results also indicated the severity of the weather has a greater effect on house losses than prescribed burning—a result also reported by Gibbons et al. (2012) and Price and Bradstock (2012). The ability of prescribed burning to modify the behaviour of subsequent wildfire diminishes with the severity of weather (Gale et al. 2023). From a study after the 2003 Alpine fires in southeastern Australia, Tolhurst and McCarthy (2016) found that the effect of prescribed burning on reducing the severity of fire was minimal where the FFDI was above 50. Collins et al. (2023) found the efficacy of prescribed burning persisted in extreme weather but only where previous burns were <3 years old and only at a local (rather than landscape) scale, which is consistent with our results. That the effect of prescribed burning diminishes with weather conditions is an important consideration given most house losses during wildfires in Australia occur at or above the 99.5th percentile for FFDI values recorded in a given region (Blanchi et al. 2010).

There are other variables known to reduce the risk of house loss during wildfires that were not measured in our study. The degree to which the house was defended, house design, construction and materials are associated with house losses (Price et al. 2021; Troy et al. 2022). While the nearest mapped vegetation formation upwind from houses was not included in the top-ranked base model, other aspects of vegetation, such as plant species composition, structure and moisture content, are known to affect fire behaviour (Zylstra et al. 2016) or house losses during wildfires (Gibbons et al. 2018). Thus, these variables should not be discounted as important additional factors that could affect the efficacy of prescribed burning.

Conclusion

Our results suggest prescribed burning—where the objective is to protect houses—is only associated with fewer house losses during wildfires when undertaken within 3 km in the upwind direction from which wildfires typically arrive and no longer than every 5 years. Most prescribed burning occurs further than 3 km from houses for logistical reasons. At distances greater than 3 km from houses, prescribed burning will only reduce house losses where it stops wildfires from reaching houses.

Previous burning had less effect on reducing house losses during wildfires than reducing woody vegetation within 40 m of houses. Our findings, therefore, cast doubt over the effectiveness of prescribed burning as currently practised in southern Australia and suggest other strategies (e.g. modifying vegetation close to houses, house design, building houses where they have a lower risk of loss, early evacuation) should be considered in addition to, or instead of, prescribed burning when mitigating the effects of wildfires on houses and lives.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s42408-025-00413-z>.

Supplementary Material 1.

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Authors' contributions

PG, GJC and MAM conceived the study, PG and MGG completed the data analyses, and PG, GJC, MGG and MAM wrote and edited the manuscript.

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Data availability

The dataset generated and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare no competing interests.

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