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Ross A. Bradstock
University of Wollongong, rossb@uow.edu.au

Owen F. Price
University of Wollongong, oprice@uow.edu.au

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We investigated the effect of fuel age on the truncation of spread of unplanned fires using a set of 1473 patches in the Sydney region of Australia. Twenty-two percent of patches derived from prescribed fire experienced a subsequent unplanned fire within 5 years, compared with 42% of patches derived from unplanned fires. Among those encounters, the subsequent unplanned fire stopped at the leading edge of 18% of prescribed patches and 11% of unplanned patches. In comparison, the subsequent fire stopped somewhere in the patch for 44% of both prescribed and unplanned fires. Overall, there was a 10% chance that a prescribed burn patch would experience an unplanned fire that stops within the patch. Statistical modelling revealed that the presence of a road barrier was the best predictor of the likelihood of stopping on the leading edge, but fuel age and weather also had an influence. Stopping on the trailing edge was less influenced by the variables analysed. In extreme weather, even 1-year-old patches have a low likelihood of stopping unplanned fires. Fuel age had little influence on the spread of unplanned fires. Consequently, prescribed fires will be most effective when sited at the urban interface where resultant reduced unplanned fire intensity will be a benefit.

Keywords

region, australia, fuel, effect, age, spread, fire, sclerophyll, forest, sydney

Disciplines

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The effect of fuel age on the spread of fire in sclerophyll forest in the Sydney region of Australia

Owen F. Price[A,B] *and Ross A. Bradstock*[A]

[A]Centre for Environmental Risk Management of Bushfire, University of Wollongong, Wollongong, NSW 2522, Australia.
[B]Corresponding author. Email: oprice@uow.edu.au

Abstract. We investigated the effect of fuel age on the truncation of spread of unplanned fires using a set of 1473 patches in the Sydney region of Australia. Twenty-two percent of patches derived from prescribed fire experienced a subsequent unplanned fire within 5 years, compared with 42% of patches derived from unplanned fires. Among those encounters, the subsequent unplanned fire stopped at the leading edge of 18% of prescribed patches and 11% of unplanned patches. In comparison, the subsequent fire stopped somewhere in the patch for 44% of both prescribed and unplanned fires. Overall, there was a 10% chance that a prescribed burn patch would experience an unplanned fire that stops within the patch. Statistical modelling revealed that the presence of a road barrier was the best predictor of the likelihood of stopping on the leading edge, but fuel age and weather also had an influence. Stopping on the trailing edge was less influenced by the variables analysed. In extreme weather, even 1-year-old patches have a low likelihood of stopping unplanned fires. Fuel age had little influence on the spread of unplanned fires. Consequently, prescribed fires will be most effective when sited at the urban interface where resultant reduced unplanned fire intensity will be a benefit.

Additional keywords: bushfire risk, fire management, prescribed burning.

Introduction

Unplanned fires (wildfires) present a serious risk to life and property at the urban interface of Sydney (Gill *et al*. 2003), as they do in many other parts of the world (Keeley *et al*. 1999). In recent years the average loss of houses in Australia is ∼84 per annum, which is an economic cost on a similar scale to cyclone and earthquake damage (McAneney 2005). Manipulation of fuel via prescribed burning is one of the major management strategies used to reduce unplanned fire risk in the Sydney region (Bradstock *et al*. 1998*a*) and throughout the world, but as Fernandes and Botelho (2003) found ‘the efficacy of prescribed fire at reducing unplanned fire risk is frequently mentioned as a matter of fact but the basic premise is seldom questioned’. In particular, the effect of prescribed burns on unplanned fires burning under extreme fire weather has not been quantified (Raison *et al*. 1983; Cheney 1994).

Prescribed fire (for fine fuel or ‘hazard’ reduction) potentially reduces the litter fuel load for several years, and thus there is an ephemeral window after treatment when there may be several possible effects on any subsequent unplanned fire that encounters the treated patch. The rate of spread and intensity of the unplanned fire may be reduced, often to such an extent that fire fighters are able to control the fire in that area. This phenomenon is supported by widespread theoretical and empirical evidence (McArthur 1962; Luke and McArthur 1977; Cheney 1994; Fernandes and Botelho 2003; McCarthy and Tolhurst 2004; Gould *et al*. 2007). Fuel reduction may also reduce the occurrence of spotting (Grant and Wouters 1993) and the likelihood of ignition (Cheney 1994). However, it is recognised that there is uncertainty over the effectiveness of fuel reduction under extreme fire weather (Raison *et al*. 1983).

This study focuses on another effect: that patches with low fuel age may stop an unplanned fire, thus directly influencing its spread and ultimate size (Gill and Bradstock 1999). There are documented cases where unplanned fires stopped in low-age fuel created through prescribed burning (Rawson *et al*. 1985; Underwood *et al*. 1985; Grant and Wouters 1993). However, these studies of prescribed fire effectiveness have used small samples (no more than 10), selected because they were effective, and hence effectiveness could not be quantified in a probabilistic sense. Moreover, most of the effective cases had fuels that were less than 1 year old.

There is controversy over the use of prescribed fire (Conroy 1996), due to the possible deleterious effects on biodiversity of frequent burning (Catling 1991; Morrison *et al*. 1996), the occasional escape of prescribed fires (Bradstock *et al*. 1998*a*) and negative perceptions of fires among the community (Jasper 1999). Nevertheless, extensive application of prescribed burning is widely advocated as the principal means of risk mitigation (Clack 2003; Doogan 2006). Given this controversy, empirical insights into fuel-age effects on risk are needed. As Bradstock (2003) noted, the principal knowledge gap in relation to unplanned fire risk is the lack of understanding of how unplanned fires are influenced by management actions.

Prescribed fires are actually a minor source of low fuel-age patches in the Sydney region, because unplanned fires currently burn a much greater proportion of the region than do prescribed fires. To be comprehensive, an analysis of fuel-age effects should

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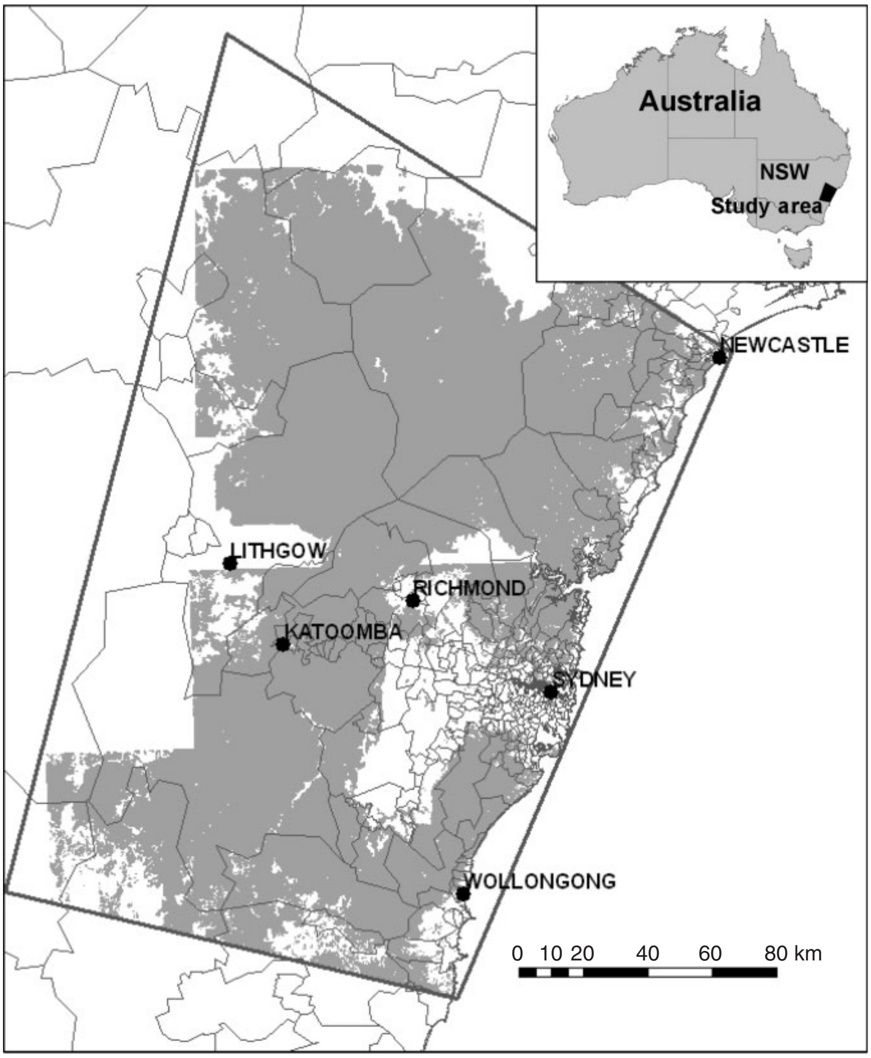

Fig. 1. The study area. Forested areas are shaded, and postcode boundaries are included to give an impression of population density.

include both sources of patches. Indeed, prescribed fires may not be as effective in terms of fuel reduction as unplanned fires, because prescribed fires usually burn with lower intensity and do not remove as much fuel (Raison *et al*. 1983; Morrison *et al*. 1996). A comparison between the efficacy of prescribed and unplanned fires would help to determine whether prescribed burns are less effective in influencing the progress of unplanned fires.

The availability of fire history mapping (of prescribed and unplanned fires) provides an opportunity to use statistical methods to investigate the effects of fuel age. In the present study, we use a sample of over 1400 fires (New South Wales Department of Environment and Climate Change, unpubl. data) to estimate empirically the chance that unplanned fires were impeded when they met previously burnt patches of differing age and type (prescribed or unplanned fire). Our emphasis was on estimating the probability of fuel age impeding the spread of unplanned fires as this information is required to form a comprehensive understanding of risk to values such as adjacent properties. We also used Geographical Information Systems (GIS) layers of vegetation type, topography and roads and daily weather records for Sydney to examine their effects as covariates of fuel age as predictors of stopping success. This study used a similar approach to a previous study of the effectiveness of fire breaks at stopping fire in the savannas of northern Australia (Price *et al*. 2007).

Methods

Study area

The study focussed on the forested coastal and mountainous hinterland of Sydney, stretching from Wollongong to Newcastle in central New South Wales (NSW; Fig. 1). The total area is 40 090 km^2. The dominant vegetation type in the region is dry sclerophyll eucalypt forests and woodlands (Keith 2004). Rainforests, wetlands, heathlands and grasslands represent only minor components of the vegetation (<2% each, Tozer *et al.* 2006). There are also large areas cleared for urban or agricultural uses, so that the forested component is 19 200 km^2. The forests are mostly located on heavily dissected sandstone plateaux tablelands within National Parks, although some are within managed State Forests and private land.

Data

The historical fire data comprise GIS layers created annually for unplanned fires and prescribed fires, extending back to 1991 (drawn from a series extending back to the 1960s; NSW Department of Environment and Climate Change, unpubl. data). Usually, the fire perimeter was drawn onto a 1 : 25 000 topographic map and then digitised. In 2001, the data were collated into a database, checked and metadata were prepared. The stated positional accuracy of the metadata was between 10 and 100 m. The data have been reviewed subsequently and found to improve in accuracy over time (de Ligt 2005), so we assumed that fires after 1990 would have low levels of error. We cross checked the alignment of fire boundaries with landscape features such as rivers and roads identified on 1 : 25 000 scale digital topographic maps (from Geoscience Australia) and found that the spatial accuracy was within 20 m. Also, we found that internal patchiness was mapped for 8 of the 16 years we used and these 8 years constitute 94% of the area burnt by unplanned fires over the period (1991–2006 fire seasons). We also checked our interpretation of the results of 26 randomly selected cases (i.e. where an unplanned fire burned though a patch of known time since last fire status) from the Blue Mountains district. This was done in consultation with the chief fire officer, whose tenure spanned the relevant time period (J. Tolhurst, pers. comm.). He confirmed that the fire mapping accurately described either what he remembered or what most likely happened in all cases.

All of the prescribed and unplanned fires from a 10-year period (fire seasons 1991–92 to 2000–01) were used as the sample, with several exceptions. Patches smaller than 1 ha were not used. To reduce pseudoreplication, where two or more patches from the same year had a common boundary, only the largest one was used. In 18 cases it was impossible to determine how the patch influenced subsequent unplanned fire behaviour, usually because the unplanned fire boundary was poorly mapped. The total sample was 1473, comprising 671 prescribed and 802 unplanned fires, which was 73% of all the mapped fires.

For each patch, several measures relating to the behaviour of subsequent unplanned fires (up to the 2005–06 fire season) on the boundary of the patch were recorded: (1) whether an unplanned fire ever reached the leading edge of the patch; (2) if so, the fuel-age; and (3) whether it stopped at the leading edge (failed to burn any of the patch) or (4) stopped on the trailing edge (stopped somewhere within the patch). Using this definition, all leading-edge successes were also trailing-edge successes. The minimum fuel age assigned was 1 year, meaning the patch experienced an unplanned fire in the fire season following that in which it burnt. In reality this may have been as little as 6 months or as much as 18 months, depending on the exact timing of the two fires. We did not include fire-meets-patch events where both fires occurred in the same fire season (July to June) because we could not determine which fire occurred first. Where an unplanned fire ignited within a previous fire patch, we assigned a leading-edge failure. If this fire remained contained within the fire patch we assigned a trailing-edge success.

A range of biophysical variables were also calculated for each patch using ArcMap 9.2 GIS tools (Environmental Systems Research Institute, Redlands, CA, USA) including: the dominant vegetation, aspect, slope, topographic position, and whether a road formed the boundary between the patches. Vegetation was derived from the 1 : 100 000 vegetation map of south-east NSW by Tozer *et al.* (2006). We used the map to define broad vegetation types of which two occurred as the dominant type in patches: rainforest and eucalypt forest. The topographic position measurements were derived from a 25-m resolution Digital Elevation Model developed from 1 : 50 000 scale, 10-m contour data by the NSW Department of Information Technology and Management, and the road information was from the 1 : 25 000 topographic map layers.

The date that the unplanned fire encountered each target patch was estimated by reference to remotely sensed hotspot data from the NOAA-AVHRR sensor (National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer; Flannigan and Vonder Haar 1986), which consists of point information, to the nearest km, of where fire activity was present in the night following any date. These data were obtained from Geoscience Australia (https://acres.ga.gov.au/noaa_data, accessed February 2008). In approximately one-third of the cases, dating was not possible, either because the hotspot data was not available before 1998 or because the assessment was ambiguous (e.g. the nearest hostpot was more than 3 km from the patch boundary).

For dated encounters, the weather record was interrogated to obtain weather measurements. Data from three weather stations (Sydney, Richmond and Katoomba) were used and events were allocated to the closest station except that any within 10 km of the ocean were assigned to Sydney to account for coastal weather patterns. A lapse rate of 0.98°C/100 m was applied to the temperature readings for events that had a different elevation to their assigned station.

The weather data has previously been adapted by Hennessy *et al.* (2005) to calculate daily values of the McArthur Mark 5 Forest Fire Danger Index, (Noble *et al.* 1980) and the Mount Soil Dryness Index. Forest Fire Danger Index is a function of wind speed, temperature, humidity and a drought factor and is routinely used to predict bushfire risk (Bradstock *et al.* 1998*a*). Soil Dryness Index is a drought index that describes how much rain would be needed to saturate a column of soil and is calculated from the number of days without rain (Mount 1972; Li *et al.* 2003). In addition to these derived variables, several raw variables were included: wind speed and humidity (all at 1500 hours) and maximum temperature. All of the variables used are listed and described in Table 1. GIS analyses were conducted using ArcMap 9.2 and extensions (ESRI 2005).

Analysis

The proportion of prescribed and unplanned fire patches that experienced a subsequent unplanned fire and the overall effectiveness at stopping were calculated, and the relationship between effectiveness and fuel age was illustrated graphically.

Table 1. Variables used in the analysis
DEM, Digital Elevation Model; FFDI, Forest Fire Danger Index; KDBI, Keetch–Byram Dryness Index; SDI, Soil Dryness Index

Variable name	Description
Fire patch	
Fire type	Planned or unplanned fire
Log area	Area of patch (natural log of ha)
Wild fire	Whether the patch experienced an unplanned fire (0 or 1)
Fuel age	Time between patch burn and subsequent unplanned fire (years)
Leading-edge stop	Whether unplanned fire stopped on leading edge (0 or 1)
Trailing-edge stop	Whether unplanned fire stopped on trailing edge (0 or 1)
Biophysical	
Topographic position	Topographic position where 0 = valley, 100 = hilltop (calculated from local maximum and minimum elevation using 1-km square moving windows on a 25-m resolution DEM)
Slope	Mean slope of the patch (derived from DEM)
Aspect	Dominant aspect quadrant (NE, SE, SW, NW)
Road	Whether a road formed the boundary (on the leading edge for leading edge analysis or trailing edge for trailing edge analysis) (0 or 1)
Vegetation	Simple vegetation type with the largest area in the patch: 1 = moist (rainforest, riparian), 2 = dry schlerophyll forest. Derived from Tozer *et al*. (2006).
Weather variables	
Maximum temperature	Maximum temperature (°C) on date
Humidity	1500 hours humidity on date
Wind speed	1500 hours wind speed on date
Drought factor	Drought factor calculated using the SDI method on date
FFDI	Forest fire danger calculated using the KDBI method on date

We focussed on patches with 5 years or less time since fire because many studies suggest that this is the approximate duration of effective fuel reduction (Adams and Simmons 1994; Morrison *et al*. 1996; Anon. 2003; Gould *et al*. 2007).

For those fire patches that experienced a subsequent unplanned fire (at any fuel age), we constructed generalised linear models (McCullagh and Nelder 1983) for the factors influencing stopping on the leading and trailing edges separately. As approximately one-third of patches had no weather data associated with them, the analysis was conducted twice: once with the whole sample but without weather variables and once with the relevant subset including the weather data.

Binomial models were constructed (response variable of 0 or 1) yielding an equation predicting the probability of stopping unplanned fires. Explanatory variables were grouped as patch variables, biophysical variables and weather variables. For each group, all possible models were compared using Akaike's Information Criterion (AIC) (Burnham and Anderson 2002) to identify the best model and any others that were supported (i.e. $\Delta AIC < 2$). Then, using the same method, a combined model was derived, including all of the variables in the best model for each group. The best model for this combined analysis was considered to be the final model. This modelling approach identifies the relative contribution of the three groups of variables to the likelihood of stopping plus those variables that have a strong influence on stopping *v.* those that are substitutable for others.

The deviance and percentage of null deviance captured were used to assess the overall goodness of fit of each model presented, and the strength of the relationships for each variable in the final model was indicated by the *Z*-value for the estimate. In this analysis, we tested two interaction terms among the patch group of variables: namely the fuel age–fire type and log area–fire type interactions. These were specifically targeted to test the hypotheses: (1) that fuel takes longer to recover following unplanned fire than following prescribed fire; and (2) that this effect would mostly be evident for large unplanned fire patches. The modelling was conducted in the R statistical package (version 2.5.0; R Development Core Team 2007).

Results

During the years of this study (i.e. fire seasons 1990–91 to 2006–07) an annual mean of 7912 ha (0.41%) of the forested part of the study area was burnt by prescription and 94 389 ha (4.92%) by unplanned fires. The mean area of the prescribed fire sample (i.e. excluding those smaller than 1 ha) was 128.3 ha and the median was 18.9 ha, whereas unplanned fires were larger on average (mean 842.2 ha), although most were slightly smaller than prescribed fires (median 15.6 ha). The sample of patches that experienced an unplanned fire represented a relatively even spread of fuel ages (at least 40 cases for each age up to 10 years), and initial fire year (at least 30 for each year 1991–2000), but the 2001–02 fire season contributed almost half of the subsequent unplanned fires. Of the 671 prescribed fire patches, 333 subsequently experienced an unplanned fire (59.6%), but only 151 of these were within 5 years (22.5%). Of the 802 unplanned fires, 486 (60.6%) experienced a subsequent unplanned fire and 337 (42.0%) were within 5 years.

For the 151 prescribed fire patches that met an unplanned fire within 5 years, the unplanned fire stopped at the leading edge in 27 cases (17.9%) and at the trailing edge (i.e. somewhere within the patch) in 67 cases (44.4%). Even for 1-year-old fuel patches

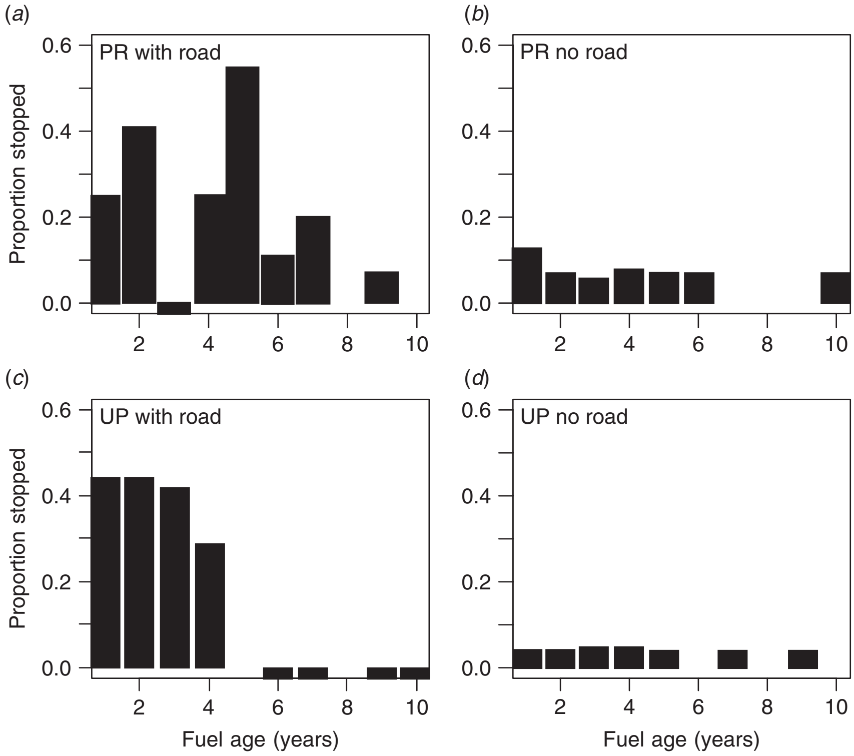

Fig. 2. The proportion of prescribed and wildfire patches that stopped subsequent wildfires on the leading edge, grouped by fuel age. Prescribed fires with road on boundary (*a*); prescribed fires with no road (*b*); wild fires with road (*c*); wild fires with no road (*d*). For fuel ages displaying a bar below zero on the *y*-axis, the sample size was less than 5 and so the proportion stopped was not calculated.

($n = 40$), the success rate at the leading edge was 17.5%. For the 337 unplanned fire patches that experienced an unplanned fire within 5 years, it stopped at the leading edge in 36 cases (10.7%), and at the trailing edge in 148 cases (43.9%). After 5 years since the patch was burnt, the percentage of unplanned fires that stopped decreased to ~4% for both prescribed and unplanned fires at the leading edge but to ~20% at the trailing edge.

The presence of a road had a profound effect on stopping success on the leading edge but not the trailing edge. For prescribed fires that experienced an unplanned fire within 5 years, 34% of the fires stopped on the leading edge where there was a road, compared with only 8% where there was no road. For unplanned fire patches, the success was 41% with a road and only 5% without. The success on the trailing edge for prescribed fires was 41% with a road and 39% without and for unplanned fire patches the success was 54% with a road and 40% without. The relationships with fuel age for patches with and without roads are shown in Fig. 2 for leading-edge events and Fig. 3 for trailing-edge events.

The generalised linear models analysis for the leading edge without weather variables revealed that both biophysical and patch attributes influence stopping likelihood, but biophysical attributes more so (as judged by either the ΔAIC or deviance captured for the best model for each group, Table 2). The final model contained fuel age, log area, vegetation type, road, and topographic position, and of these, road had the strongest relationship (assessed using the *Z*-value of the estimate, Table 3). Unplanned fires were more likely to stop if the burnt patch was recent, large (particularly for unplanned fire patches), with a low topographic position, but mostly if a road occurred on the boundary. The final model and the individual terms fuel age and topographic position were highly significant ($P < 0.001$), but the model captured less than 25% of the total deviance. This means that most of the factors influencing fire stopping were not explained.

In the leading-edge model with weather, the patch model was the same as the model without weather but the biophysical model was slightly different (Table 2). The biophysical model had the best goodness of fit, followed by the patch model, with the weather model having much lower goodness of fit. Unplanned fires were less likely to stop under low humidity. The best of the combined models contained all the variables present in the group models, and had a slightly improved goodness of fit compared with the model without weather, capturing 28.8% of the null deviance. In this final model the log area term was not statistically significant, slope and the log area–fire type interaction were significant at the $P < 0.05$ level and the other four terms were significant at the $P < 0.01$ level (Table 3). The presence of a road gives an approximate threefold increase in the likelihood of stopping irrespective of fuel age (Fig. 4*a*). The log area–fire type interaction showed that the highest likelihood of stopping subsequent unplanned fires occurs in large unplanned fire patches, followed by large prescribed burns, small prescribed burns and then small unplanned fires (Fig. 4*b*). The model equation predicts

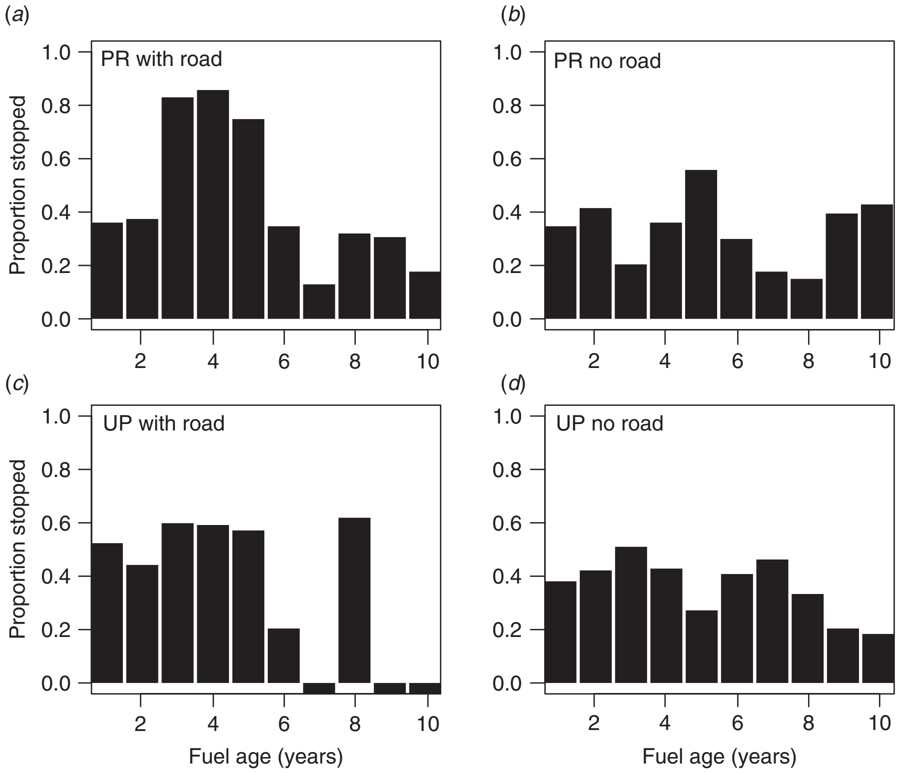

Fig. 3. The proportion of prescribed and wildfire patches that stopped subsequent wildfires on the trailing edge, grouped by fuel age. Prescribed fires with road on boundary (*a*); prescribed fires with no road (*b*); wild fires with road (*c*); wild fires with no road (*d*). For fuel ages displaying a bar below zero on the *y*-axis, the sample size was less than 5 and so the proportion stopped was not calculated.

that the maximum likelihood of a fire stopping, in favourable weather conditions and with a road and fuel age of 1 year, is ~0.3.

The modelling results for the trailing edge without weather were weaker than the leading edge. The patch variables had slightly stronger relationships than the biophysical variables and the best combined models contained the same variables except for the addition of fire type and a fire type–log area interaction in the trailing-edge model (Table 2).

For the trailing edge with weather, the patch model had a stronger fit than the biophysical or weather model (which were similar) (Table 2). The patch model contained fuel age, log area, fire type and both the interaction terms. The weather model selected drought factor, humidity and maximum temperature, but there were many alternative models with other weather variables. The best combined model contained all of those selected in the group models except vegetation type, and captured 16.6% of the deviance. In this final model, the fuel age term is positive and not significant whereas the fuel age–fire type interaction is negative and highly significant. This means that the probability of fires stopping on the trailing edge is reduced over time, but only for unplanned fire patches. The fitted values of this relationship are illustrated in Fig. 5. The estimates for maximum temperature and dominant vegetation were not significant, whereas those for topographic position and the log area–fire type interaction were highly significant (at $P < 0.001$). In comparison to the leading edge (Fig. 4), the likelihood of stopping is higher, and less influenced by the variables analysed here.

Discussion

The present study demonstrated that fuel age only has a limited probabilistic effect on the propagation of unplanned fires in the Sydney region. This is partly because ~20% of the prescribed fire patches and 41% of unplanned fire patches experience an unplanned fire within 5 years, and partly because low fuel-age patches rarely stop subsequent fires. The statistical models demonstrate that the presence of a road has the biggest influence on stopping success on the leading edge and that none of the variables studied here had much influence on stopping at the trailing edge. Moreover, where the unplanned fires are burning under strong winds, low humidity or during drought, the low fuel-age patches are even less effective. These are the conditions when a stopping effect will be critical to asset protection (Bradstock and Gill 2001).

Low fuel-age patches rarely experience an unplanned fire because unplanned fires are rare themselves: as less than 5% of the forested area is burnt by unplanned fires each year, it follows that by chance alone only 25% of low fuel-age patches would be expected to experience an unplanned fire within 5 years (i.e. 5% × 5 years).

Table 2. Results of model selection process

The table shows the best model and alternative models (Akaike's Information Criterion, ΔAIC < 2 compared to the best) for four analyses each comprising two or three classes of predictor variables and a combined model. ΔAIC refers to the difference compared to the best combined model. FFDI, Forest Fire Danger Index

Dependent	Model	Model term	AIC	ΔAIC	Deviance captured	Null deviance (%)	Probability
Leading edge	No weather						
Patch	Best	Fuel age + Log area + Fire type + Log area–Fire type	462.35	61.34	53.73	10.6	<0.001
	Alt 1	Fuel age + Log area + Fire type	463.44	62.43	50.64	10.0	<0.001
	Alt 2	Fuel age + Log area	463.71	62.70	48.37	9.6	<0.001
Biophysical	Best	Topographic position + Vegetation + Road	428.39	27.38	90.23	17.7	<0.001
Combined	Best	Fuel age + Log area + Vegetation + Road + Topographic position	401.01	0.00	121.61	23.8	<0.001
	Alt 1	Fuel age + Log area + Fire type + Vegetation + Road + Topographic position + Log area–Fire type	401.24	0.23	125.38	24.5	<0.001
	Alt 2	Fuel age + Log area + Road + Topographic position	402.09	1.08	118.53	23.2	<0.001
Leading edge	Weather						
Patch	Best	Fuel age + Log area + Fire type + Log area–Fire type	257.05	36.61	37.97	13.3	<0.001
	Alt 1	Fuel age + Log area + Fire type + Log area–Fire type + Fuel age–Fire type	257.99	37.55	39.03	13.7	<0.001
Biophysical	Best	Topographic position + Vegetation + Slope + Road	251.21	30.77	43.81	15.4	<0.001
	Alt	Topographic position + Vegetation + Road	252.26	31.82	40.76	14.8	<0.001
Weather	Best	Humidity + Wind speed	274.71	54.27	16.31	5.7	<0.001
	Alt 1	Humidity	275.44	55.00	13.58	4.8	<0.001
	Alt 2	Max temp + Humidity	276.28	55.84	14.74	5.2	<0.001
	Alt 3	Max temp + Humidity + Wind speed	276.16	55.72	16.87	5.9	<0.001
Combined	Best	Fuel age + Log area + Fire type + Log area–Fire type + Topographic position + Road + Humidity	220.44	0.00	80.58	28.3	<0.001
	Alt 1	Fuel age + Log area + Fire type + Log area–Fire type + Topographic position + Road + Humidity + Wind speed	220.52	0.08	83.82	29.4	<0.001
	Alt 2	Fuel age + Log area + Fire type + Log area–Fire type + Topographic position + Road + Humidity + Vegetation	221.01	0.57	83.01	28.8	<0.001
Trailing edge	No weather						
Patch	Best	Fuel age + Log area + Fire type + Log area–Fire type	1013.1	43.54	90.1	8.2	<0.001
	Alt 1	Fuel age + Log area + Fire type + Log area–Fire type + Fuel age–Fire type	1014.4	44.84	90.3	8.3	<0.001
Biophysical	Best	Topographic position + Vegetation + Road	1036.6	67.04	62.8	5.7	<0.001
	Alt 1	Topographic position + Vegetation + Road + Aspect	1037.8	68.24	67.6	6.2	<0.001
Combined	Best	Fuel age + Log area + Fire type + Logarea–Fire type + Topographic position + Vegetation + Road	969.56	0.00	137.8	12.6	<0.001
	Alt	Fuel age + Log area + Fire type + Log area–Fire type + Topographic position + Road	970.9	1.34	134.5	12.3	<0.001
Trailing edge	Weather						
Patch	Best	Fuel age + Log area + Fire type + Fuel age–Fire type + Log area–Fire type	627.76	40.79	63.75	9.4	<0.001
	Alt 1	Fuel age + Log area + Fire type + Log area–Fire type	629.62	42.65	58.89	8.8	<0.001
Biophysical	Best	Topographic position + Vegetation	655.33	68.36	30.18	4.4	<0.001
	Alt 1	Topographic position + Vegetation + Road	656.06	69.09	31.45	4.6	<0.001
Weather	Best	Humidity + Drought factor + Maximum temperature	656.11	69.14	31.40	4.6	<0.001
	Alt 1	Humidity + Drought factor + Maximum temperature + Wind speed	657.06	70.09	32.45	4.8	<0.001
	Alt 2	Humidity + FFDI	657.02	70.05	28.49	4.2	<0.001
	Alt 3	Humidity + Maximum temperature + FFDI	657.35	70.38	30.16	4.4	<0.001
	Alt 4	Humidity + Drought factor + FFDI + Maximum temperature	657.48	70.51	32.03	4.7	<0.001
Combined	Best	Fuel age + Log area + Fire type + Log area–Fire type + Fuel age–Fire type + Topographic position + Maximum temperature + Drought factor + Humidity	586.97	0.00	112.54	16.6	<0.001
	Alt 1	Fuel age + Log area + Fire type + Log area–Fire type + Fuel age–Fire type + Topographic position + Vegetation + Maximum temperature + Drought factor + Humidity	587.74	0.77	113.77	16.7	<0.001
	Alt 2	Fuel age + Log area + Fire type + Log area–Fire type + Fuel age–Fire type + Topographic position + Drought factor + Humidity	588.08	1.11	109.43	16.1	<0.001

Table 3. Final models, showing the coefficients and goodness of fit measures for the best combined model for each of the four analyses
UP, unplanned

Term	Estimate	SE	*Z*-value	*P*-value
Leading edge, no weather				
Intercept	−1.8861	0.5000	−3.772	0.000
Fuel age	−0.1751	0.0513	−3.413	0.001
Log area	0.2875	0.0625	4.601	0.000
Vegetation type 2	−0.5332	0.3018	−1.767	0.077
Topographic position	−0.0238	0.0076	−3.106	0.002
Road	2.1036	0.2804	7.501	0.000
Leading edge, with weather				
Intercept	−1.0647	0.8228	−1.294	0.196
Fire type UP	−2.2276	0.8312	−2.680	0.007
Log area	−0.0960	0.1536	−0.625	0.532
Fuel age	−0.2650	0.0752	−3.524	0.000
Fire type UP (log area)	0.5296	0.1817	2.915	0.004
Road	1.7392	0.3984	4.366	0.000
Humidity	0.0345	0.0097	3.566	0.000
Topographic position	−0.0275	0.0102	−2.681	0.007
Trailing edge, no weather				
Intercept	1.3979	0.4225	3.309	0.001
Fuel age	−0.0754	0.0265	−2.842	0.004
Fire type UP	−1.2946	0.3563	−3.633	0.000
Log area	0.0348	0.0657	0.529	0.597
Fire type UP (log area)	0.3619	0.0837	4.326	0.000
Vegetation type 2	−0.3508	0.1911	−1.836	0.066
Topographic position	−0.0253	0.0044	−5.693	0.000
Road	0.3333	0.1725	1.932	0.053
Trailing edge, with weather				
Intercept	2.4954	1.0107	2.469	0.014
Log area	−0.0964	0.0828	−1.165	0.244
Fuel age	0.0269	0.0579	0.464	0.643
Fire type UP	−1.1932	0.5848	−2.040	0.041
Fire type UP (log area)	0.5829	0.1105	5.275	0.000
Fire type UP (fuel age)	−0.1457	0.0769	−1.895	0.058
Maximum temperature	−0.0405	0.0230	−1.763	0.078
Drought factor	−0.0774	0.0361	−2.143	0.032
Humidity	0.0168	0.0068	2.484	0.013
Topographic position	−0.0262	0.0059	−4.461	0.000

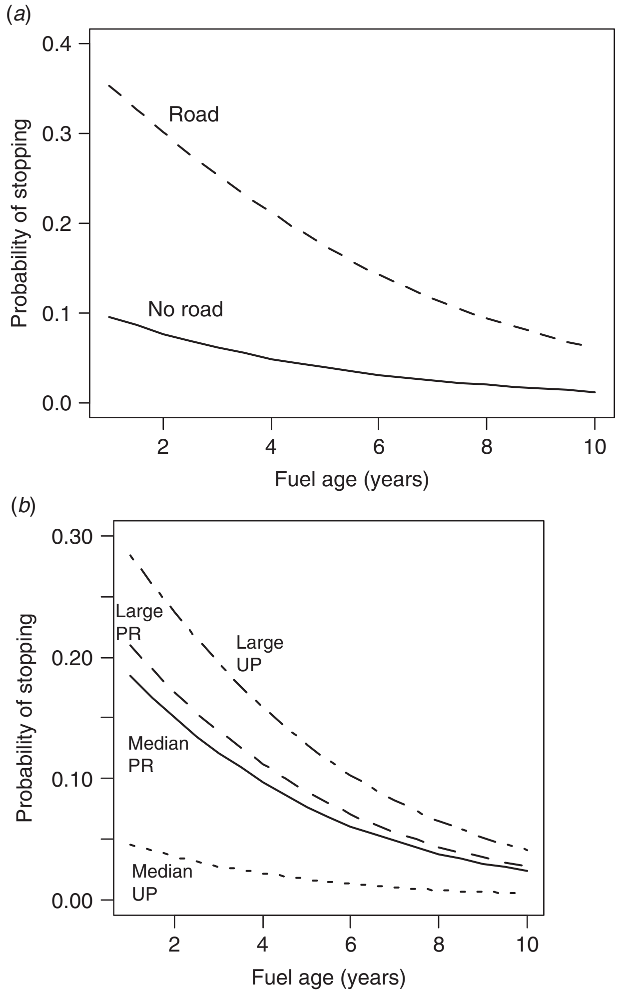

Fig. 4. Fitted equations for the final model on the leading edge including weather variables against fuel age: comparing patches with and without roads on their leading edge (*a*); comparing fire type (unplanned, UP; or prescribed, PR) and fire area (*b*), where the area is either the median for all fires (22 ha) or in the upper 2% of areas (3000 ha). In each graph, terms not illustrated are held at their median values.

When an unplanned fire does encounter a low fuel-age patch, it is unlikely to stop at the leading edge, and if there is no road, there is less than 10% chance that an unplanned fire will stop. There have been previous studies that report unplanned fires being stopped by prescribed burns. For example, Rawson *et al.* (1985) reported three cases where unplanned fires were stopped in forested parts of Victoria, but two of these were burnt less than 2 months before the unplanned fire, and the third was ~1 year before. Likewise, the cases reported by Grant and Wouters (1993) were burnt only a few months before the unplanned fire, as were the majority of the cases studied by Underwood *et al.* (1985). These studies were selective samples of cases where prescribed fires were known to affect subsequent unplanned fires, in contrast to this study, which sampled a large number of low fuel-age patches, irrespective of whether they stopped fires or not, allowing the probability of effectiveness to be quantified.

Stopping success decreases with fuel age, which is due to the regrowth of fuels. Fuel accumulation has been studied in many situations, and the results vary. Some studies from forests in south-eastern Australia report that fine fuels are back to significant levels (i.e. likely to lead to fire intensities that are unsuppressable) after between 3 and 5 years (Conroy 1996; Adams and Simmons 1994; Morrison *et al.* 1996; Anon. 2003; Gould *et al.* 2007). The present study suggests that the modest effect of fuel reduction on ability to stop a subsequent unplanned fire is essentially gone after 5 years.

The trailing edge was approximately three times more effective at stopping unplanned fires than the leading edge. The present study has not adequately explained why this is so, but it has revealed that fuel age is not a major factor. The greater effectiveness of the trailing edge may be due to the effect of suppression or simply to chance. Fire fighters will use the trailing edge of a reduced fuel-age patch rather than the leading edge because of the lower fire intensity of the fire in the patch. Probably, most of the unplanned fires in our study were fought, but there are no data with which to identify which of the 1500

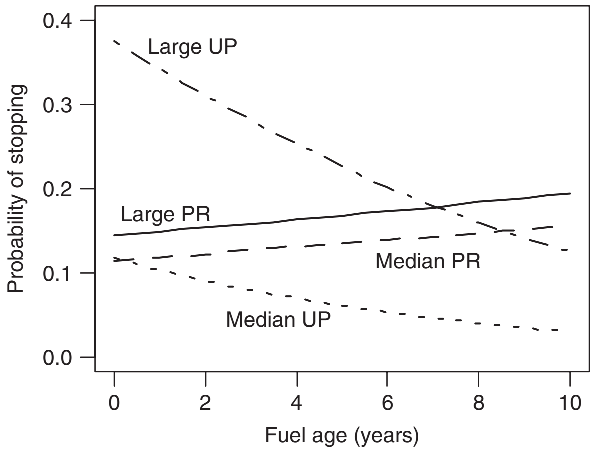

Fig. 5. Fitted equations for the final model on the trailing edge including weather variables against fuel age: comparing fire type (unplanned, UP; or prescribed, PR) and fire area, where the area is either the lower quartile (small, 6 ha) or the upper quartile of fire sizes (156 ha).

events involved suppression. If suppression was a major factor, then trailing-edge success would have been lower in the absence of suppression, so in effect, our study has identified the upper limit or most optimistic estimation of effectiveness. Thus, it does not change the general conclusion that fuel age does not have much influence on stopping unplanned fires.

The other possible explanation for the higher effectiveness of the trailing edge is that there is a reasonable probability that the unplanned fire will stop somewhere in the patch by chance alone. This probability is presumably related to the relative size of the unplanned fire and the reduced fuel patch: if the unplanned fire is small and the patch is large, there is a high chance that the unplanned fire boundary will fall within the patch. In our sample, the mean area ratio of unplanned fire to patch was ~50, but for 87% of those where the ratio was 5 or less ($n = 107$) the unplanned fire stopped within the patch. This suggests that chance does have a role. Not only that, it suggests that there is a 'background' level of stopping chance that is not influenced by the attributes studied here. This may explain why success remains at 25% even for patches with fuel ages of 10 years or more, whether with or without a road barrier. If this background level of fire stopping were removed, then the residual trailing effectiveness is not much greater than the leading-edge effectiveness.

The fact that roads had a strong effect on the leading edge but not on the trailing edge may also be related to suppression. Fire fighters often light backing fires from roads toward an advancing fire, and are likely to site the backing fire where a reduced fuel patch on the other side of the road will reduce the chance of the fire spotting.

Large unplanned fire patches were more effective than large prescribed fire patches at stopping unplanned fires. This is probably at least partly due to the chance effect discussed above. However, it may also be because large unplanned fires burnt more intensely and had a stronger fuel-reduction effect than the prescribed fires.

The weather effects revealed here are only approximate because the weather data used was not the actual weather experienced at the fire front, but abstracted because the timing of the encounters was not known precisely and the weather station was removed from the fires. It is likely that the statistical relationships would be stronger if fire-ground weather could be used and the percentage of deviance captured by the models would be improved.

Although low fuel-age patches are not highly effective at stopping fires, there is a considerable body of evidence that patches produced by prescribed fire reduce the intensity of subsequent unplanned fires (McArthur 1962; Luke and McArthur 1977; Cheney 1994; Gould *et al.* 2007) and their rate of spread (McCarthy and Tolhurst 2004; Gould *et al.* 2007). Under extreme weather conditions, unplanned fires may not be controllable unless they have been recently burnt (Grant and Wouters 1993). Thus, it is sensible to place prescribed burns in areas where maximum advantage can be gained from fire suppression of subsequent unplanned fires: that is, primarily close to the assets that need to be protected. Current approaches to fire management in the region have targeted the bulk of prescribed burning at the urban edge (Anon. 2006).

Given the low likelihood of stopping unplanned fires, it follows that prescribed burns will have a small effect on minimising the overall area burnt over a fire season. This conclusion is supported by macro-scale analyses (Gill and Moore 1997 in Western Australia and Brewer and Rogers 2006 in the USA) that correlated annual regional values for the area burnt by unplanned fire with the area burnt by prescribed fire. Therefore, to have a substantial effect on unplanned fire area, a very considerable proportion of the landscape would need to be treated. This conclusion has been reached by several previous modelling studies based on well-established fire spread equations, both in Australia (Bradstock *et al.* 1998*a*, 1998*b*; King *et al.* 2006, 2008) and elsewhere (Pinol *et al.* 2005; Cary *et al.* 2009).

The present study also throws light on the broader question of the consequences of fire suppression that removes many of the smaller unplanned fires. It has previously been proposed (at least in the USA) that the reduction in small patches has resulted in larger, catastrophic unplanned fires because fuel ages become homogenised and thus don't provide any hindrance to unplanned fire (Minnich and Chou 1997). However, this argument is contested by others (Keeley *et al.* 1999; Keeley and Fotheringham 2001). The present study suggests that for south-eastern Australia there would be little effect of removing small unplanned fires because the low fuel-age patches these fires would have created would pose little hindrance to unplanned fires anyway.

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