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Discussions

The spatial domain of wildfire risk and response in the Wildland Urban Interface in Sydney, Australia

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Abstract

In order to quantify the risks from fire at the Wildland Urban Interface (WUI), it is important to understand where fires occur and their likelihood of spreading to the WUI. For each of 999 fires in the Sydney region we calculated the distance between the ignition and the WUI, the fire weather and wind direction and whether it spread to the WUI. The likelihood of burning the WUI was analysed using binomial regression. Weather and distance interacted such that under mild weather conditions, the model predicted only a 5 % chance that a fire starting more than 2.5 km from the interface would reach it, whereas when the conditions are extreme the predicted chance remained above 30 % even at distances further than 10 km. Fires were more likely to spread to the WUI if the wind was from the west and in the western side of the region. We examined whether the management responses to wildfires are commensurate with risk by comparing the distribution of distance to the WUI of wildfires with roads and prescribed fires. Prescribed fires and roads were concentrated nearer to the WUI than wildfires as a whole, but further away than wildfires that burnt the WUI under extreme weather conditions (high risk fires). 79 % of these high risk fires started within 2 km of the WUI, so there is some argument for concentrating more management effort near the WUI. By substituting climate change scenario weather into the statistical model, we predicted a small increase in the risk of fires spreading to the WUI, but the increase will be greater under extreme weather. This approach has a variety of uses, including mapping fire risk and improving the ability to match fire management responses to the threat from each fire. They also provide a baseline from which a cost-benefit analysis of complementary fire management strategies can be conducted.

1 Introduction

Knowledge for estimating and mitigating risk from wildfires is most critical at the Wildland Urban Interface (WUI): the boundary between flammable vegetation and

the houses and other assets in the urban land (Safford et al., 2009; Mell et al., 2010). As urban populations expand, so do the number of houses in the WUI in Australia (Hughes and Mercer, 2009) and in the USA (Schoennagel et al., 2009), and house losses increase accordingly (Schoennagel et al., 2009). The probability of loss
5 (consequential risk) is a conditional function of ignition, spread and the vulnerability of urban environments and structures (Bradstock and Gill, 2001). Much of the emphasis on risk research is on the latter (Bhandary and Muller, 2009; Blanchi et al., 2010). The risk consequences of ignition and spread have a strong spatial component that awaits more formal scrutiny (i.e. the chance of a fire reaching the WUI given the location of its
10 ignition). This is important because management options for the treatment of fuel and co-location of measures for facilitating suppression (i.e. road, track networks) need to carefully positioned in landscapes in order to be effective.

   Choices about where to position these management activities are made heuristically. In many jurisdictions, management is a bet hedging exercise based, with varying
15 mixtures of treatments and access focussed at the WUI and in the wider landscape. In some jurisdictions, these are mandated by planned zoning systems. An understanding of the likelihood that any ignition will result in a fire that reached the WUI, based on its location, distance and environmental context (e.g. weather at the time) from the WUI, will yield insight into the likely efficacy of current and future configurations of
20 management actions (prevention and suppression). For example, there is little benefit in treating fuels 10 km away from the WUI if most of the wildfires ignite only 5 km away. This insight will also be important for planning responses to changing human development patterns and future fire weather. In addition, such an understanding will inform residents of the risks they face (Stockmann et al., 2010) and provides an
25 essential source of information for decision analysis of optimal management strategies.
   This study therefore examined:

   1. The relationship between distance and the chance that an ignition will result
      in a fire reaching the WUI, and the way that weather conditions influence this

chance. This leads to a spatially explicit domain of "likelihood", which is largely unquantified in many parts of the world.

2. The degree to which the distribution of current road and fuel treatment networks conform with spatial gradients of likelihood, as defined above.

3. The degree of change in likelihood of fire spreading to the WUI under climatic change.

Sydney in south-eastern Australia was chosen as the study area. Sydney has a long WUI and highly flammable forest vegetation abutting the WUI in many places. As a result, houses have been destroyed by fire in 12 of the past 43 fire seasons (1970–2013) (Ellis et al., 2004; Rural Fire Service, unpublished data).

The likelihood that a fire will reach the interface is a consequence of two factors: the likelihood that an ignition will occur in the landscape and the likelihood that it will spread to the interface. Fire history maps are invaluable for quantifying both of these factors and a probabilistic model of the chance of spread to the interface can be derived from past fires. Specifically, if the ignition points and final perimeters of fires are known, then it is possible to determine which fires reached the interface and model the probability as a function of distance between the interface and the ignition and other potential drivers. It is this aspect that we focus on in this study: the likelihood that a fire will spread to the interface. We were particularly interested in the interaction between two important drivers of risk: the distance of the ignition from the WUI and weather. There are other drivers of the risk of spread, in particular the load and distribution of fuels, but at present, we lack the data and methods to address these.

This study is the first to quantify from empirical data, the likelihood that fires originating outside will spread to the WUI. It is also the first to examine the effect of individual fires on the WUI using a large sample. Previous studies of fire risk in the WUI have either examined the effects of a single fire on house loss (Bhandary and Muller, 2009; Brillinger et al., 2009); used measures of fire regime (such as the number of fires over a period; Haight et al., 2004); simulated fires (Stockmann et al., 2010;

Bar Massada et al., 2009) or have abstracted risk to some extent (such as measuring how intense a fire would be if it occurred, Bradstock et al., 1998).

2 Methods

2.1 Study area

Greater Sydney is a city of 4.7 million people (Australian Bureau of Statistics figures, unpublished data[1]), lying in a highly developed coastal lowland plain (the Cumberland Plain) surrounded by dissected sandstone tablelands (Fig. 1). The native vegetation in the tablelands is largely intact and is dominated by a diverse dry and wet sclerophyll eucalypt forest, with a total area of approximately 20 000 km^2. Rainforests, wetlands, heathlands and grasslands represent only minor components of the vegetation (< 2 % each, Tozer et al., 2006). Urban development abuts the forest around the edge of the city and there are fingers of development into the tablelands. There are also many forested patches within the city, usually associated with steep and rugged drainage lines. The WUI in the Sydney region has a length of approximately 7000 km (from the data derived in this study). The climate is warm and temperate, and the rainfall total of 1200 mm is evenly distributed through the year (Bureau of Meteorology data for Sydney Airport). An average of 5 % of the forest is burnt by unplanned fires each year, though up to 20 % can burn in one year, and another 1 % is burnt by prescribed burning (Price and Bradstock, 2011). Houses are lost to unplanned fires in approximately one quarter of years (Ellis et al., 2004).

2.2 Data

We used the New South Wales Digital Cadastral Database (www.lpi.nsw.gov.au/mapping_and_imagery/spatial_data/cadastral_data, accessed July 2007) to define

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[1]www.abs.gov.au

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urban areas as those where there were more than 2 properties per ha (using a 1 ha grid size). Then we defined the WUI to be a 500 m buffer around those urban areas. The total perimeter of the urban area thus defined was 7672 km, or 6303 km if only urban patches larger than 10 ha are included. The 500 m buffer corresponds to the Strategic Fire Advantage Zone used in bush fire risk management plans in NSW (Anonym, 2008). We used this buffer zone as the interface rather than the actual edge of the urban areas to reduce the possible underestimation of the number of fires that reached the WUI caused by fire suppression, which is usually most active right at the urban edge. We were unable to estimate the proportion of fires that may have been stopped by suppression, due to lack of appropriate information. We refer to this zone as the WUI buffer. 27 % of all fires were recorded as starting within the WUI buffer, and these were excluded from the analysis.

Several aspects of the geography vary within the study region. Since the main urban centre of Sydney is approximately in the centre of the region, the dominant direction between the interface and the forest varies among the compass sectors. The relative amount of forest compared to other land uses varies and the east has a more coastal influence. To control for the possibility that these differences may alter fire behaviour, we divided the region into four geographic zones (NE, SE, SW and NW) and also included wind direction (N, S, E or W) in the analysis.

Ignition locations and perimeters of all unplanned fires from the years 1977–2008 were derived from mapped fire history records and incident reports provided by the New South Wales Office of Environment and Heritage (OEH) (unpublished data). Each ignition was assigned to one of five nearest Bureau of Meteorology weather stations: Nullo Mountain, Mount Boyce, Cessnock, Moss Vale and Richmond (mean distance 43 km). Then, by cross-referencing with the ignition date, the Forest Fire Danger Index (FFDI) (McArthur, 1967) and the wind-direction at 3 p.m. were recorded. FFDI reflects both the current weather conditions (via coefficients for daily temperature, humidity and wind speed) and medium term rainfall (via the Drought Factor coefficient). It is commonly used to measure the risks associated with current fires in Australia, and

has been shown to be a good predictor of fire spread and the occurrence of large fires in this region (Price and Bradstock, 2010; Bradstock et al., 2009). The fire danger rating system classifies an FFDI below 5 as "low" and an FFDI between 50 and 75 as "severe". Many of the ignitions had missing attributes due to missing date recordings or gaps in the weather records. There were 2615 fires with known ignition points and 999 cases with sufficient data to analyse. The variables are described in Table 1a.

The distances to the WUI buffer of the centroids of all 3112 prescribed burns during the same period were calculated. Centroids are the geographical centre of a feature, which is the actual centre for a regular polygon such as a square but can be outside a convoluted polygon. They are a good measure of the location of prescribed burns as the median size of patches was 14.0 ha. Thus no part of the patch is likely to be more than 200 m away from the centroid. Distance to the WUI buffer was also calculated for the centroids of all road segments (273 000 segments of mean length 236 m). To provide a control set of distances, we calculated the distance to the WUI buffer of all 1 million points in a regular grid with 200 m separation across the study area. Features with a distribution of distances less than the control set are biased toward the buffer. The cumulative distribution of distances was calculated for each of these features, including wildfire distance and the distance of wildfires that actually burnt the WUI buffer and ignited on days with an FFDI $\geq$ 50. The threshold of 50 reflects the findings of Blanchi et al. (2010) that 93 % of house loss in Australia occurs on such days. We refer to this set of fires as high risk fires. These five datasets are described in Table 1b.

2.3 Analysis

The data were explored graphically, and the underlying relationships analysed using binomial regression (McCullagh and Nelder, 1983). We used model selection techniques based on Akaike Information Criterion (AIC) to derive a best model and supported alternatives for the probability of burning the buffer (Burnham and Anderson, 2002). The response variable was whether the WUI buffer burnt or not (binomial 0 or 1) and there were five predictors: distance, FFDI, wind direction, subregion and

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a spatially-lagged response variable (SLRV): the distance weighted mean of whether all other fires burned the WUI buffer. The SLRV approach is commonly used to control for spatial autocorrelation (Haining, 2003). All the possible model combinations including two-way interactions among all of the variables except the SLRV were tested. The analysis was performed twice, with raw and with log-transformed distance values and the version with the highest explanatory power was selected for the final model. As a further exploration of the role of spatial autocorrelation, the best model with the SLRV was compared to the best model without it, and the extent of autocorrelation in the response variable (burnt or not burnt), and in the residuals from the best model with and without the SLRV were calculated using Moran's I (Haining, 2003).

The cumulative distance distribution data for each set of features (wildfires, high risk fires, prescribed fires, roads and the control set) were compared graphically and Kolmogorov–Smirnov tests were used to determine which features were significantly closer to the buffer than others via two-way comparisons of all combinations.

Hennessy et al. (2005) predicted future weather for south-eastern Australia under climate change, and produced a data set of actual and predicted future FFDI data for several weather stations using historical data. We used the data from two weather stations within the study area (Sydney Airport and Williamstown) to estimate the degree of change in the most altered scenario (IPCC 2001 A2 Scenario at 2050 timeline). We found that the predictions of daily FFDI are well described by a linear model of changed vs. current FFDI with a coefficient (slope) of 1.108 for Sydney ($r^2 = 0.989$) and 1.127 for Williamstown ($r^2 = 0.992$). A linear relationship was a better fit than a logarithmic or quadratic relationship. We used the mean of the two coefficients to calculate an adjusted FFDI for each of the fires in the database (i.e. an 11 % increase on current FFDI values). These adjusted FFDI values were substituted for the observed values under current climate in the equation of the best model for burning the WUI buffer, and the predicted probabilities were used to calculate the distance travelled and the likelihood that they would reach the WUI buffer under projections of climate change.

3 Results

For the sample of 999 fires, the median distance from the ignition point to the WUI buffer was 2.5 km, though almost 30 % were closer than 1 km and 8 % were further than 20 km (Fig. 2a). The majority of fires ignited on days with an FFDI below 12, but the maximum recorded FFDI was 88 (Fig. 2b). A small proportion of the fires (9.1 %) spread to burn the WUI buffer. The percentage of fires that reached the WUI buffer decreased with the distance of the ignition point from the WUI buffer: i.e. 44 % at ignition distance < 250 m to 3 % at ignition distance > 3 km (Fig. 3). The percentage of fires that reached the WUI buffer also increased with FFDI, such that at ignition distances > 3 km, the percentage of fires reaching the WUI buffer increased from zero at FFDI < 5 to 12 % at FFDI greater than 25 and (Fig. 3). Similar trends with FFDI were observed at all distance classes. Westerly winds were more common than winds from other directions (Fig. 2c) and fires were almost twice as likely to spread to the WUI buffer under westerly winds than northerly or easterly, and southerly winds were intermediate (percentages burnt: N = 4.4, E = 5.8, S = 10.2, W = 12.9). Fires were more common in the northwest and northeast subregions than in the southeast or southwest (Fig. 2d) and were much more likely to reach the WUI buffer if they originated in the northeast subregion than in the other subregions (percentages burnt: NE = 14.8, NW = 4.5, SE = 7.9, SW = 6.1).

The best model for the probability of burning the urban buffer contained Log-distance, FFDI, wind direction, subregion, the SLRV and the interaction between distance and FFDI (Table 2). There were no alternative supported models. The model captured 35.8 % of null deviance. The model predicted that the probability of the WUI buffer burning reduces very rapidly with distance (Fig. 4). When FFDI is 25 or less, the probability falls almost to zero at distances above 2 km (Fig. 4a). When FFDI is 50, the probability falls much more slowly, and remains at about 0.2 even at distances exceeding 10 km. When FFDI = 75, the probability remains at high at all distances. The wind direction effect in the model reflected the raw data: westerly winds resulted in approximately twice the probability of burning the WUI buffer than

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easterly or northerly winds across all distances and FFDI levels (Fig. 4b). Among the subregions, the northwest and southwest regions had higher likelihoods of fires reaching the WUI buffer, and the southeast has lower (compared to the northeast) (Fig. 4c). Neither subregion nor wind direction showed an interaction with FFDI or

5 distance. The northeast subregion had the highest likelihood of reaching the WUI (14.8 % cf. 4.5 % for NW, 7.8 % for SE and 6.3 % for SW), but this was because ignitions tended to be closer than for other regions (mean distance 1870 m, cf. 11 300 m for NW, 1880 m for SE and 8120 m for SW). When distance and weather were controlled for, this region was at relatively low risk (Table 2).

10 When the SLRV was excluded, the analysis still selected all of the other terms from the SRLV-included model and their coefficients and p values were almost unchanged (for example, the distance estimate changed from −1.222 to −1.246, and the FFDI estimate from −0.072 to −0.074). This model captured 30.7 % of the null deviance. The Moran's I test revealed strong spatial autocorrelation in the raw burnt values ($I =$

15 0.481, $z = 4.551$, $p < 0.000$), and the residuals from the best model without the SLRV. However the residuals from the model with the SLRV were not spatially autocorrelated ($I = −0.112$, $z = 1.05$, $p = 0.29$).

The distribution of locations of ignition points of wildfires, prescribed fires and roads was closer to the WUI buffer compared with the control sample. Prescribed fires and

20 roads were located closer to the WUI buffer than wildfires, but high risk fires (FFDI > 50 that burnt the WUI buffer) were the closest of all (Fig. 5, Table 3). While only 20 % of the control points were within 2 km of the WUI buffer, 44 % of wildfires, 59 % of prescribed fires and 79 % of high risk fires were within this distance. These differences in distances were confirmed by the two-way Kolmogorov–Smirnov tests, which indicated that all fire

25 types were closer to the WUI buffer than the control sample (significant at $p < 0.01$).

Under a projected future climate (i.e. Hennessy et al., 2005), a higher proportion of fires were predicted to reach the WUI buffer (Table 4). However, the change was small (6.3 % increase overall), and increased as a function of the FFDI value in the original data. For current FFDI days below 5, the model predicted a 0.29 % increase in the

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future likelihood that a fire would reach the WUI buffer, whereas when current FFDI was above 50, then the increase was 14.8 %.

4 Discussion

The likelihood that a fire will reach the WUI decreases with distance, but this relationship is strongly conditioned by weather so that in extreme weather all fires pose a risk to the WUI, irrespective of how far away the ignition is. To reinforce this unfortunate reality, one of the fires that killed many people in Victoria in 2009 spread more than 40 km in 6 h (Teague et al., 2010).

The WUI is a focus for fire activity and management in the Sydney region. The road network and prescribed fires are concentrated there, but so are wildfires in general and fires that burn the WUI in particular. Comparing the distance distributions of these elements, the focus of management is reasonably well aligned with the risk (i.e. they are slightly biased toward the WUI compared to ignition locations of wildfires in general). However, when we consider that the great majority of high risk fires started within 2 km of the WUI, it may be argued that an even greater concentration of management near the interface is warranted. When compared to the western USA where only 11 % of treatments were within 2.5 km of the WUI (Schoennagel et al., 2009), prescribed fires as a fuel reduction treatment are well targeted in Sydney (59 % within 2 km).

Fire managers have a heuristic understanding of the nature of fire spread, but the quantification allows the effects of weather and ignition location to be partitioned. For example, the level of risk from an ignition 400 m away under an FFDI of 5 is the same as one 1 km under an FFDI of 25, and one 10 km away under an FFDI of 50. The results also provide a formal basis for evaluation of the management activities (i.e. roads, fuel treatment) in relation to ignition and the chance of fires spreading to the urban interface. This will be an important ingredient for future cost-benefit analyses of fire management strategies.

To date, there have been few attempts to conduct cost-benefit analyses that compare different prevention and suppression options (Penman et al., 2011). Ideally, an adaptive management framework would be used to measure how these risks respond to different management strategies. However, in the short term, this study could be used to calibrate fire simulations models, which are then used to conduct "experiments" exploring the effects of different levels of suppression effort, prescribed burning treatments or other strategies on the risk of fires burning the interface. Simulation models have been used in this way (Finney et al., 2007; Stockmann et al., 2010), but the applications usually lack an empirical calibration. Most of the current tools for predicting fire behaviour use mathematical models developed under a limited range of experimental conditions and have not been thoroughly validated against wildfires (Sullivan, 2009). As such they give an imperfect prediction of risk. In contrast, this study quantifies the likelihood of spread based on a large number of real wild fires, including some very large ones (the largest was 87 000 ha).

In Sydney, fires were more likely to burn the interface if the wind was westerly. This is presumably because large fires burn predominantly from west to east (as suggested by Cunningham, 1984), which is a consequence of typical synoptic patterns over south-eastern Australia in summer (Foley, 1947). It is interesting that this effect is apparent in the models even in the presence of FFDI, which captures wind-speed effects. This probably reflects the inability of FFDI to capture the entire weather effect. Alternatively it could be because there is more forested land to the west of the WUI in Sydney compared to the east. The eastern regions are more urbanised and so protected by urban land and are bounded to the east by the sea (so fewer fires originate there). Fires are also more likely to burn the interface in the southwest and northwest, with approximately twice the likelihood of the other sub-regions. As with wind direction, this may reflect the tendency of westerly winds to bring worse fires or the relative exposure to forest. There was no interaction between either subregion or wind direction with FFDI or distance, which means the differences among subregions and wind directions are consistent for all weather conditions and distances.

The study provides an empirical basis for assessing how risk may change under future conditions (e.g. climate change). The predicted increase under climate change in likelihood of spread to the WUI was very small under low danger fire weather, but considerable under extreme fire weather. A 15 % increase over a current likelihood of 31 % for FFDI > 50 represents a risk that fire management agencies should be making contingency plans for. This prediction is in broad agreement with climate change predictions for other fire attributes. For example, Bradstock et al. (2012) found a 30 % increase in simulated annual burnt area by 2050 in the same region and using the same projections of future changer in FFDI as the current study. However, across the world, predictions of the response of wildfire to climate change are highly variable (Flannigan et al., 2009).

As a quantification of the base-rate of fire risk, this study has some shortcomings. Suppression activity was carried out on many of these fires, which probably affected their chances of reaching the WUI buffer. We partially controlled for this by using a buffer 500 m away from the actual urban edge because much of the suppression effort is concentrated between here and the edge which is where the assets are located. Nevertheless, it is likely that some of the fires that had the potential to burn the buffer were prevented from doing so. This may be particularly true for fires on low FFDI days, because these fires can quickly be controlled and remain small. Thus, we have estimated the risk of spread under the average suppression regime operating between 1977 and 2008, and may have underestimated the risk from fires on low FFDI days if there were no suppression. In order to burn from the ignition point to the WUI buffer, each of the fires in this study had to cross a different combination of vegetation types, recently burnt patches (reduced fuel loads) and disruptions such as roads and rivers. These would all have affected the likelihood of reaching the interface but none of these factors were captured here. This is presumably one of the main reasons why the model did not explain a greater proportion of variation. While an investigation of these factors would be a useful addition to this study, we believe there exclusion did not bias

the relationships quantified here because we used a large sample which would have included a representative range of values for each of these factors.

It is unlikely that the distance/risk relationship is the same in all parts of the interface due the differences in the shape and configuration of the interface itself. We have demonstrated that it varies at the subregional scale and that wind direction is one of the modifiers of risk. Thus, areas of the WUI that face east should be at lower risk. But there are additional factors that might be important. For example, the total risk at any place on the WUI is presumably related to the arc of exposure to flammable vegetation. An isolated development surrounded by vegetation on all sides will be at more risk than one which is mostly surrounded by urban land with a narrow arc of flammable vegetation. This effect could be explored by conducting an interface-centric analysis of fire spread, rather than the fire-centric analysis in this study.

5 Conclusions

The likelihood that a fire will reach the WUI is the result of an interaction between weather and distance, such that under mild conditions, fires have very low risk if they ignite more than 2.5 km from the interface but under extreme weather conditions, the risk is relatively high and largely independent from distance. The results of this study should be of use to fire management agencies for a number of reasons. Primarily, they provide an evidentiary basis for demarking fire management zones and for tailoring the response to fires to their predicted risk. Secondarily, they may be used as input to a cost-benefit analysis aimed at measuring the effectiveness of fire risk reduction strategies. The study has implications beyond the Sydney study region. The fuel types and fire weather in Sydney are generally similar across eastern Australia, and therefore the relationships here could be used to predict fire risk more widely. Internationally, the fuel types and weather associated with fires differ, but the general influence of fuel and weather is similar to Australia. Therefore, our approach could be used to examine the

way the chance of ignition and spread of fires ultimately determines the probability of loss of property.

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Which fires spread to the WUI

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Interactive Discussion

Table 1. Variables and datasets used in the analysis.

(a) Variables used in the Generalised Linear Modelling.			
Name	Description	Mean	Range
Dependent	Variable		
Burnt	Whether or not the fire burnt any part of the WUI buffer	0.91	0–1
Predictor	Variables		
Distance	Distance from ignition point to the nearest point in the WUI buffer (m)	5891	10–28 933
Log(Distance)	Natural log of Distance (m)	7.75	2.30–10.27
FFDI	Forest Fire Danger Index on the day of ignition	16.5	0.10–86.2
Wind_dir	Wind direction (N, S, E, W) on the day of the ignition		
Subregion	Subregions (NW, NE, SE, SW)		
SLRV	Spatially-lagged response variable: mean of all other Burnt values, weighted by distance to the current ignition	0.72	0.00–0.67
(b) Datasets used for comparing distances to the Wildland Urban Interface buffer.			
Name	Description	N	Median distance (m)
Wildfires	The known ignitions as used for the Generalised Linear Modelling analysis	999	2523
High Risk Fires	Wildfires ignited on days with FFDI > 25 and which did spread to the WUI buffer	14	406
Prescribed Fires	All prescribed fires	3112	1342
Roads	Road segments	230 000	0
Control	All points in the study area located on a grid of 200 m separation	1 000 000	5807

Table 2. Best model for predicting the probability that a fire will reach the Wildland Urban Interface (WUI) buffer ($n = 999$, Percentage of Deviance captured = 35.83, AIC = 407.14, no supported alternatives). FFDI = Forest Fire Danger Index, SLRV = spatially lagged response variable (to control for spatial autocorrelation).

	Estimate	Std. Error	$z$value	P
(Intercept)	3.898	0.963	4.049	0.000
Log(Distance)	−1.222	0.157	−7.798	0.000
FFDI	−0.072	0.031	−2.339	0.019
Wind_dir: N	−0.591	0.506	−1.167	0.243
Wind_dir: S	0.541	0.465	1.163	0.245
Wind_dir: W	0.649	0.398	1.632	0.103
Subregion: NW	0.902	0.404	2.233	0.026
Subregion: SE	−0.592	0.402	−1.473	0.141
Subregion: SW	1.084	0.538	2.016	0.044
SLRV	7.689	1.380	5.570	0.000
Log(Distance)·FFDI	0.016	0.005	3.426	0.001

Table 3. Results of the Kolmogorov–Smirnov tests for difference in distance distributions. The value is the D statistic: the maximum difference in the y axis between lines displayed in Fig. 5. All comparisons were significant at $p < 0.001$, except Wildfires vs. Control ($p = 0.002$).

	Control	Roads	Prescribed Fires	Wildfires
Roads	0.481			
Prescribed Fires	0.418	0.197		
Wildfires	0.183	0.486	0.380	
High Risk Fires	0.596	0.567	0.553	0.562

Table 4. Proportions of fires reaching the Wildland Urban Interface (WUI) buffer under different weather conditions for current and projected future climates. The column Modelled Current Climate refers to the predicted values from the preferred model and the Modelled Future Climate column used the same model, but with increased Forest Fire Danger Index (FFDI) values based on the future climate projection.

| Current FFDI | Actual | Proportion reaching WUI buffer | | % Increase |
		Modelled Current Climate	Modelled Future Climate	
All data	0.0891	0.0949	0.1009	6.32
<= 5	0.0566	0.0700	0.0702	0.29
> 5 <= 12	0.0599	0.0708	0.0717	1.27
> 12 <= 25	0.0878	0.0944	0.0977	3.50
> 25 <= 50	0.1391	0.0993	0.1133	14.10
> 50	0.2456	0.3129	0.3593	14.83
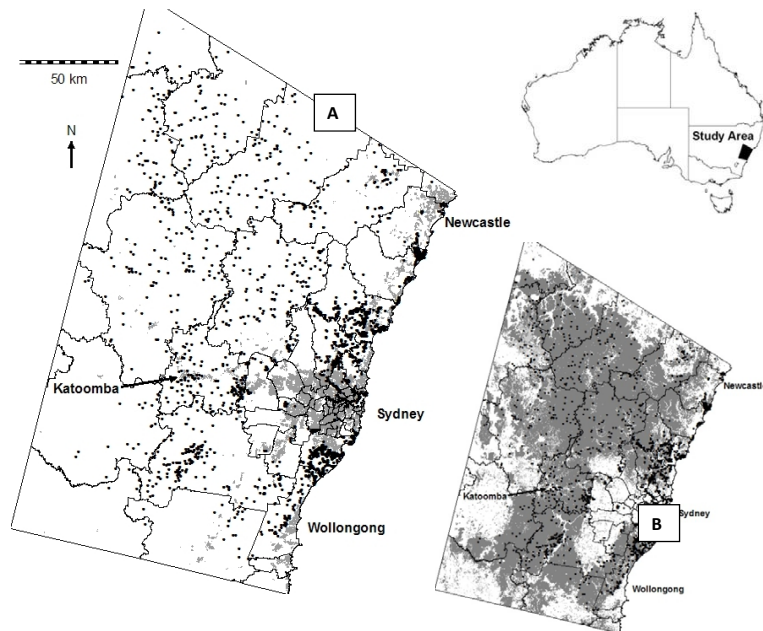
Fig. 1. The study area, showing **(A)** the ignition points of all fires and the defined urban land (grey shading) and **(B)** forested vegetation surrounding Sydney (grey shading) (Office of Environment and Heritage, unpublished data).
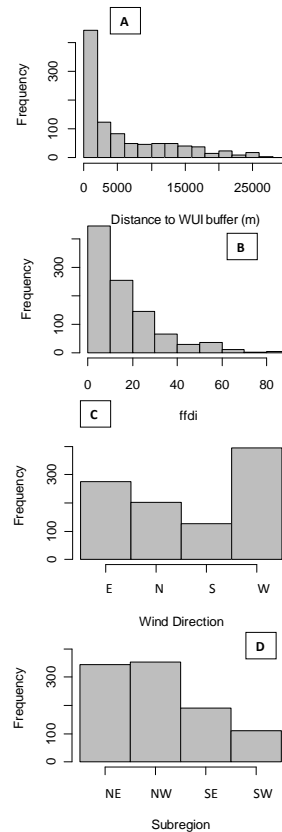
Fig. 2. Frequency histograms for the predictor variables: **(A)** distance to Wildland Urban Interface (WUI) buffer; **(B)** Forest Fire Danger Index (FFDI); **(C)** wind direction; **(D)** subregion.
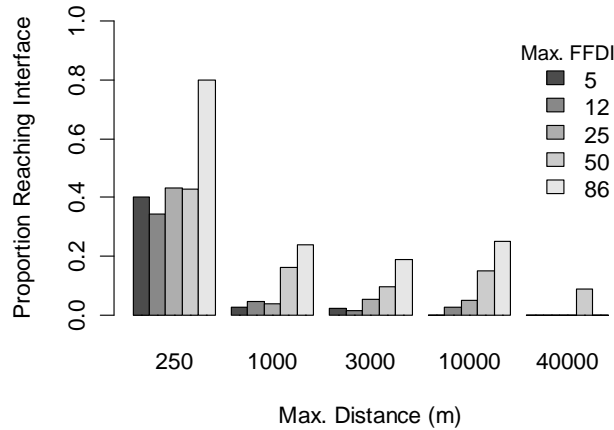
Fig. 3. The proportion of fires that burnt the Wildland Urban Interface (WUI) buffer in different distance and Forest Fire Danger Index (FFDI) classes.
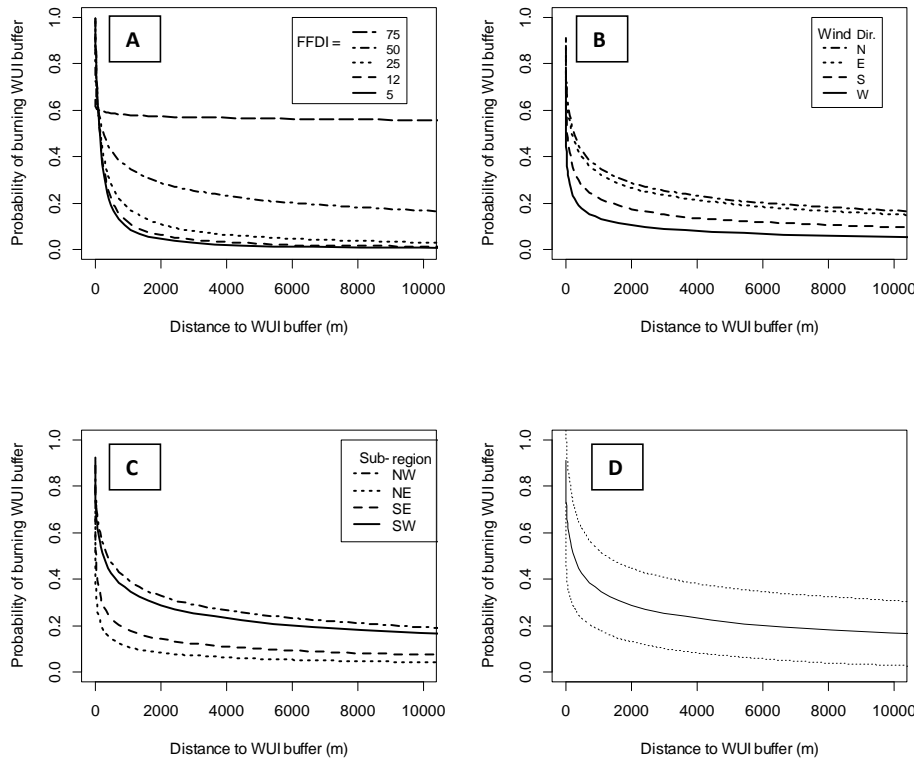
Fig. 4. Model predictions for the probability of burning the Wildland Urban Interface (WUI) buffer: **(A)** for different Forest Fire Danger Index (FFDI) values, with wind direction = west and subregion = northwest; **(B)** for each wind direction, with FFDI = 50 and subregion = northwest; **(C)** for each subregion with FFDI = 50 and wind direction = west; **(D)** mean (solid) and 95 % confidence interval (dotted) for FFDI = 50, wind direction = west and subregion = northwest.

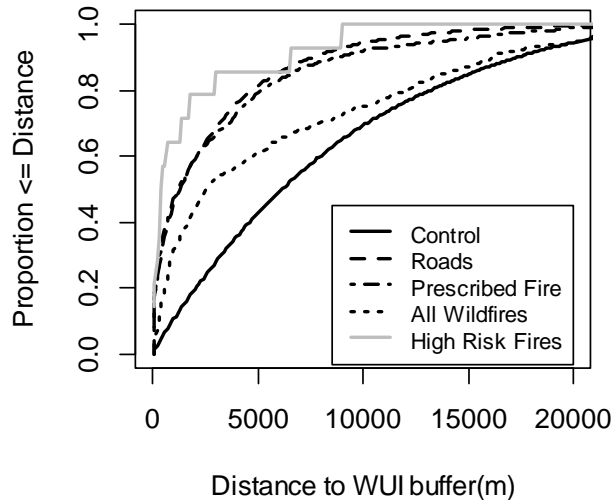**Which fires spread to the WUI**

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Fig. 5. The cumulative distribution of distance to the WUI buffer for a series of features: random landscape points; roads; prescribed fires; wildfires and wildfires that burnt the Wildland Urban Interface (WUI) buffer on days with FFDI >=50 (High Risk Fires). The *y* axis is the proportion of each feature type that is less than or equal to the defined distance on the *x* axis.