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Countervailing effects of urbanization and vegetation extent on fire frequency on the Wildland urban interface: disentangling fuel and ignition effects

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Abstract

Fire activity has been found to follow a humped relationship with population density, but the countervailing drivers and scale effects in this relationship have not previously been teased apart. This is important because it helps us to understand which aspects of fire risk are amenable to management. The likelihood of a fire occurring at the Wildland Urban Interface (WUI) can be broken into two components: that of ignitions occurring and that of the fire spreading from the ignition to the interface. We hypothesize that urbanization is a double-edged sword because it both increases the likelihood of ignition but also protects areas from fire spread. We investigated this hypothesis for Sydney Australia using 38 years of historical fire mapping by examining statistical relationships between wildfire count at 1250 points in the WUI and measures of vegetation clearing and urbanization at multiple scales (1 km and 10 km radii around sample points). The number of fires at a point was influenced negatively by the amount of un-vegetated land at both 1 km and 10 km radii and positively by urban land within 10 km radii. There was also an interaction between un-vegetated land and urbanization such that fire activity is particularly high where some urban development has occurred but a considerable amount of vegetation remains. As predicted, urban centres provide both sources of ignition and a degree of protection from fire spread. Fire risk could best be reduced either by reducing fuel near the WUI or by reducing ignitions from city dwellers.

Keywords

Bushfire, Wildfire, Fire management, Ignition

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Research Paper

Countervailing effects of urbanization and vegetation extent on fire frequency on the Wildland Urban Interface: Disentangling fuel and ignition effects

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HIGHLIGHTS

- Wildfire frequency at the urban interface is negatively related to the amount of cleared land.
- Fire frequency is positively related to the amount of urban land.
- Wildfire is particularly high in urban land retaining substantial native vegetation.
- Urban development is a double-edged sword with respect to wildfire.

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ABSTRACT

Fire activity has been found to follow a humped relationship with population density, but the countervailing drivers and scale effects in this relationship have not previously been teased apart. This is important because it helps us to understand which aspects of fire risk are amenable to management. The likelihood of a fire occurring at the Wildland Urban Interface (WUI) can be broken into two components: that of ignitions occurring and that of the fire spreading from the ignition to the interface. We hypothesize that urbanization is a double-edged sword because it both increases the likelihood of ignition but also protects areas from fire spread. We investigated this hypothesis for Sydney Australia using 38 years of historical fire mapping by examining statistical relationships between wildfire count at 1250 points in the WUI and measures of vegetation clearing and urbanization at multiple scales (1 km and 10 km radii around sample points). The number of fires at a point was influenced negatively by the amount of un-vegetated land at both 1 km and 10 km radii and positively by urban land within 10 km radii. There was also an interaction between un-vegetated land and urbanization such that fire activity is particularly high where some urban development has occurred but a considerable amount of vegetation remains. As predicted, urban centres provide both sources of ignition and a degree of protection from fire spread. Fire risk could best be reduced either by reducing fuel near the WUI or by reducing ignitions from city dwellers.

1. Introduction

Human settlements act both to increase wildfire ignition rates and to remove fuel required for fire spread as postulated by Syphard (Syphard, Radeloff, Hawbaker, & Stewart, 2009; Syphard et al., 2007) who found a humped relationship between population density and wildfire activity in Mediterranean biomes around the world. Likewise, Westerling et al. (2011) found a positive relationship between fire activity and population density in California, but in some particularly densely populated areas, fire activity was particularly low. This dual effect of human populations requires further exploration because quantifying the roles of the two effects would help us to understand how fire frequency (and consequent risk) varies across a region and how it could be reduced. Optimization of wildfire management requires a cost-benefit analysis of all management strategies, for which the first prerequisite is quantifying the independent effects of risk factors such as these. Since the impact of wildfire on human values is greatest at the Wildland Urban Interface (WUI) (Mell, Manzello, Maranghides, Butry, & Rehm, 2010; Safford, Schmidt, & Carlson, 2009), this zone should be a priority for this research.

The likelihood of a wildfire occurring at any site is determined by a complex array of factors: those that influence fire ignition and

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those that influence its subsequent spread. If humans act in countervailing ways as Syphard et al. (2009) suggest, both to increase ignition rates and to remove fuel, then it should be possible to separate these effects using measures that reflect one or other of them. For example, the extent of un-vegetated land (as measured in most vegetation maps) describes the degree of permanent fuel removal and so affects fire ignition and spread, while property density measures the potential source of ignitions. These two measures are somewhat related: vegetation clearance usually accompanies high-density development, but there are situations where the two are disconnected. For example on most farming land there are low levels of vegetation and low property density and in amenity-led rural communities where people are escaping cities to live closer to the natural environment there can be high levels of native vegetation coverage and high property density. If Syphard et al. (2009) are correct and other factors are held constant, then farming landscapes should have the lowest fire frequency and amenity-led communities the highest.

Because wildfires come in a range of sizes and people (who start many fires) are mobile, some of these factors may operate at different scales. For example, since fire-starters are mobile, we may expect the effect of urbanization on ignition to be experienced over many kilometres, but since it is the fuel at the exact site that determines whether a fire starts, un-vegetated land will influence ignition over small scales. On the other hand, large fires have to spread through extensive fuels, so spread may be influenced by the extent of un-vegetated land at a much larger scale than ignition. These matters are important: if we want to reduce the risk from wildfire we need to know whether it is better to manage fuels, people or both and whether the local, landscape or both scales are most influential.

There have been many studies that develop spatially explicit empirical models of ignition, which generally find measures related to human population to be important predictors (Liu, Yang, Chang, Weisberg, & He, 2012; Penman, Price, & Bradstock, 2013; Romero-Calcerrada, Novillo, Millington, & Gomez-Jimenez, 2008). However, the protection offered by un-vegetated land has received little empirical attention. Rather, simulation has usually been used to model fire spread towards the WUI (Atkinson, Chladil, Janssen, & Lucieer, 2010; Bradstock et al., 2012; Chuvieco et al., 2010; Keane, Drury, Karau, Hessburg, & Reynolds, 2010; Stockmann, Burchfield, Calkin, & Venn, 2010). These methods implicitly include the effects of un-vegetated land on fire spread through the use of fuel maps, but do not quantify those effects. Bradstock, Gill, Kenny, and Scott (1998) used a more simple approach, applying the McArthur fire behaviour equation to predict the frequency of days in which fires would be uncontrollable if they occurred under different hypothetical fuel reduction treatments. Most importantly, none of the methods is able to discriminate the countervailing effects of un-vegetated land or urbanization or identify scales of effect. It is possible to do this empirically, using historical fire mapping and statistical modelling.

We hypothesize that ignitions are positively related to human population density and the tendency to spread is negatively related to the amount of un-vegetated land. In other words, fire frequency associated with human development is in tension between the positive effect of population size (starters of fires) and the negative effect of un-vegetated land (removal of fuel). We expect the most effective way of reducing fire is to match high levels of un-vegetated land with low levels of urbanization, such as occurs in farming landscapes, and on the other hand, the most fire prone landscapes will be where there is high level of urbanization but relatively little un-vegetated land, such as in amenity-led communities within forests. Note that this expectation does not consider the cost effectiveness of the measures (e.g. cost per home protected) or the ecological values of native vegetation. Moreover, we predict that there are multi-scale effects such that the local extent of un-vegetated land reduces fire occurrence (ignition and spread) around houses, but there is an additional benefit from un-vegetated land at larger scale because this can protect houses from the spread of even the largest fires.

In this study, we investigate the fire frequency experienced at points in the WUI in the Sydney region of Australia. We focused on the WUI rather than the entire region because the WUI is both the area where impacts on human values are most acute and also where the tension between un-vegetated land and population is most likely to be manifest. Sydney experiences damaging fire seasons that cause house loss once or twice per decade (Bradstock et al., 1998), and in this respect is similar to many other cities in Australia and elsewhere in the world (Keeley, Fotheringham, & Morais, 1999). We sampled points in the WUI and constructed statistical models of fire count against a range of spatial predictor variables. The primary objective was to understand how the spatial pattern of un-vegetated land and urbanization influences fire frequency. In order to do so, we also explored and controlled for other potential drivers such as geology, vegetation type, and topography.

2. Methods

2.1. Study area

Sydney is a city of 4 million people, 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). Approximately 5% of the forest is burnt by unplanned fires each year, and another 1% is burnt by prescribed burning (Price & Bradstock, 2011).

2.2. Data

We used the 2007 New South Wales Digital Cadastral Database to define urban areas as those where there were more than two properties per ha (using a 1 ha grid size). Then we defined the WUI to be a 500 m buffer around the 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. This urban layer has a major concentration in the city of Sydney, with smaller urban centres in Wollongong and Newcastle (Fig. 1). Notice that WUI exists within the city area due to the prevalence of retained forest in some suburbs, and also the presence of small or linear urban areas away from the coastal area (e.g. Katoomba).

To create a sample for analysis, we created points every 500 m along a line 250 m outside the urban lands (i.e. at the mid-point of the WUI). These points were all 250 m from urban land, but could be located among low-density housing or farming land. Alternating points were used for model development (n = 633) and for model validation.

An historical fire-mapping database produced by the Office of Environment and Heritage was used to calculate the number of fires experienced at each point over a 38 year period (1970–2008).

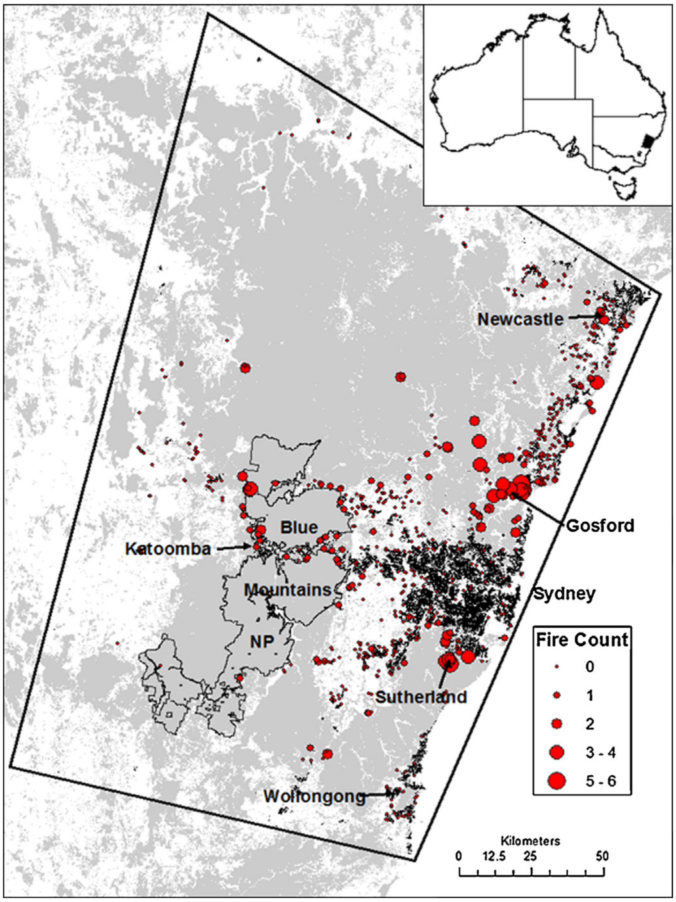

Fig. 1. The study area showing the fire count at the 638 sample points used for analysis. Black shading is urban land, grey is native vegetation (mostly forest), white is neither urban or vegetated (largely agricultural). The outline defines the Blue Mountains National Park, one of several forest dominated protected areas, and major towns are also indicated.

Vegetation information was derived from a map of the native vegetation formations of NSW (Keith, 2004). Fire and vegetation maps have locational accuracy of approximately 100 m. The vegetation map includes a class for cleared land (no native vegetation), and this was used to calculate the proportion of un-vegetated land in a circle around each point at two radii: 1 km and 10 km. Notice that as well as urban land, non-native vegetation can contribute to the un-vegetated land estimate, and this may comprise gardens or farm land. The percentage of urban land was calculated at the same radii (using the urban land layer defined above). To capture the effects of prevailing fire-weather wind directions, the direction between each point and the closest patch of un-vegetated land of at least 150 ha was calculated. Direction was expressed both as a compass class (NE, SE, SW or NW) and as the angle between NW and the direction (i.e. a point protected from the NW = 0, from the SW = 180).

Several variables were also used to control for other sources of variation in the fire regime. Vegetation type was identified from the Keith (2004) map as the dominant type within 250 m of each point. The classes were simplified into Dry Sclerophyll, Wet Sclerophyll plus Heath, and other. The choice of classes was based on preliminary analysis that resulted in lumping together vegetation classes with similar effects on fire count. 57% of the points were located in un-vegetated patches, and of the vegetated ones, 93% were in treed vegetation (forest or woodland). Geology at the sample point was defined as sandstone or other (derived from 1:250,000 map). Topographic variables elevation, slope and aspect were calculated from a 30 m resolution Digital Elevation Model from Geoscience Australia. Lengths of roads and rivers (inside a 250 m radius circle) were calculated from Geoscience Australia's 1:25,000 topographic map layers. The variables used are listed in Table 1.

2.3. Analysis

We undertook exploratory analyses by plotting bar graphs of mean fire frequency vs. bucketed values of the predictor variables and calculating a correlation matrix of all the variables. The correlations were used to check that the predictor variables were sufficiently independent of each other to be included in the subsequent analysis. We also explored the interaction between un-vegetated land and urban extent through three-dimensional plots.

Correlations between predictor variables were sufficiently low to allow their inclusion in modelling analyses (Table 2): the highest being between No-veg_1 km and No-veg_10 km ($r = 0.62$). However, we had originally intended to include un-vegetated land and urban extent measures with 2 km, 5 km and 20 km radii, but we discarded them because they were too closely correlated with the 1 km and 10 km measures ($r > 0.7$).

Generalized linear modelling (GLM) was used to explore fire count using the selected set of predictor variables. A Poisson error distribution and log link function were assumed, and because the sample was dominated by zero fire count values, a subset of the data was used consisting of the 118 points that had experienced any fires and 144 randomly selected points with no fires. The best model and alternative supported models were identified using model selection techniques based on the AIC (Burnham & Anderson, 2002) of all possible model combinations plus all two-way interactions between un-vegetated land and urban extent variables. Supported alternatives were also noted. Fire count was potentially spatially autocorrelated, and this was addressed by adding a Spatially Lagged Response Variable (Haining, 2003) to the final model: the distance weighted mean of the fire counts of all other points (Neighbour Count). The degree to which this method had reduced the spatial autocorrelation was examined by comparing Moran's I for the residuals of the model with and without this variable. The goodness of fit was assessed using a pseudo-r^2 based on log-likelihood values (Magee, 1990) and the contribution of each variable was assessed by the change in pseudo-r^2 when it was removed from the model.

Two more analytical methods were used to improve confidence in the identified relationships. Zero-inflated Poisson regression was applied to the full sample (i.e. without selecting a subset of zero fire count points), with the same model development process as for the GLM model. This method compensates for the over-representation of zero values in the response variable (Cameron & Trevedi, 1998). A regression tree analysis was also performed with the same predictor variables. Regression trees can be useful for identifying non-linear or threshold relationships (De'ath & Fabricius, 2000). All analyses were conducted in R statistical software (R Core Development Team, 2007), using packages 'pscl' and 'tree'.

3. Results

The sampled values for Fire Count in the WUI showed hotspots around Gosford and Sutherland (Fig. 1), which are both areas where large population centres abut extensive native vegetation. Smaller hotspots occurred in the Blue Mountains, near Katoomba.

Several of the predictor variables showed relationships with fire count, revealed in the bar-plots (Fig. 2). No-veg_1 km, No-veg_10 km, and River Length had negative relationships, Slope had a positive relationship and Urban_1 km and Urban_10 km had no obvious relationships (possibly unimodal). The three-dimensional

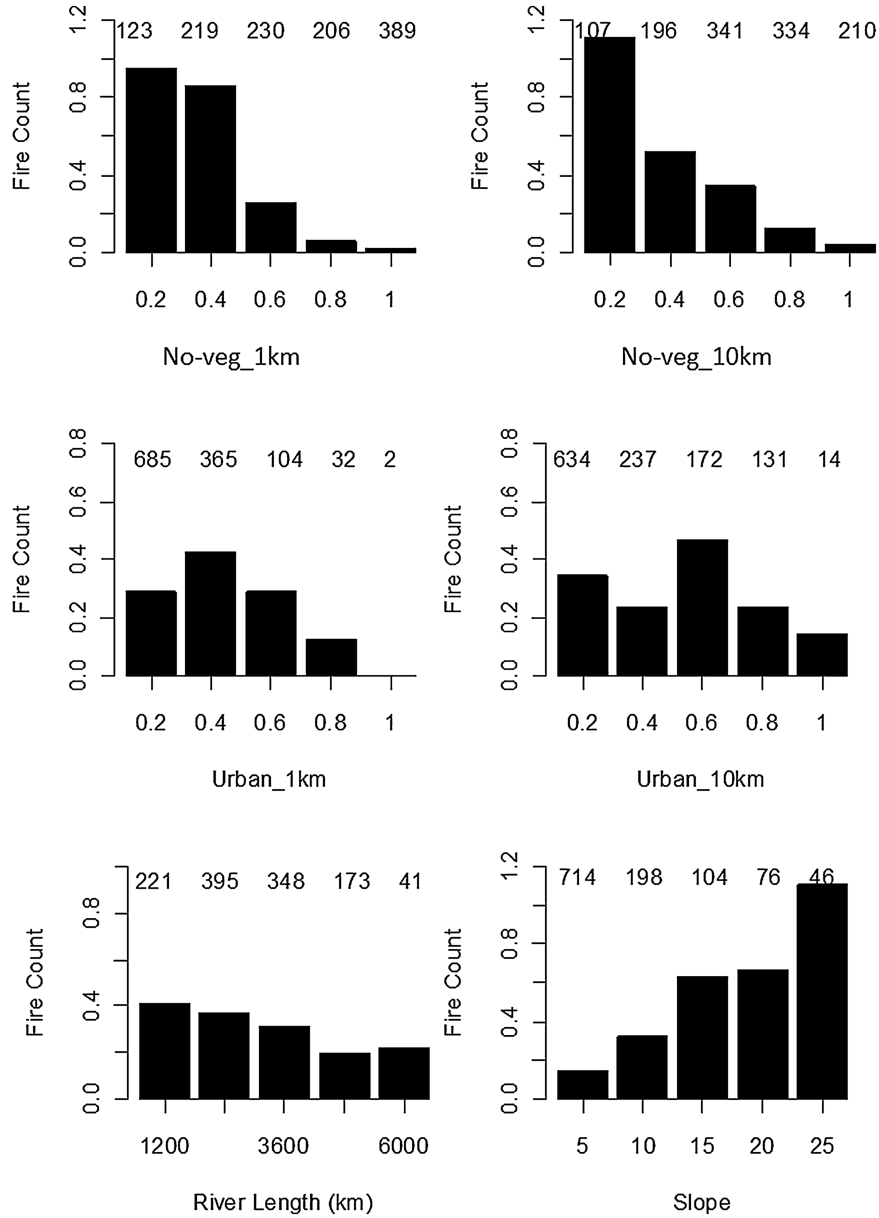

Fig. 2. Mean fire count for a range of predictor variables. Sample sizes are included above the bars.

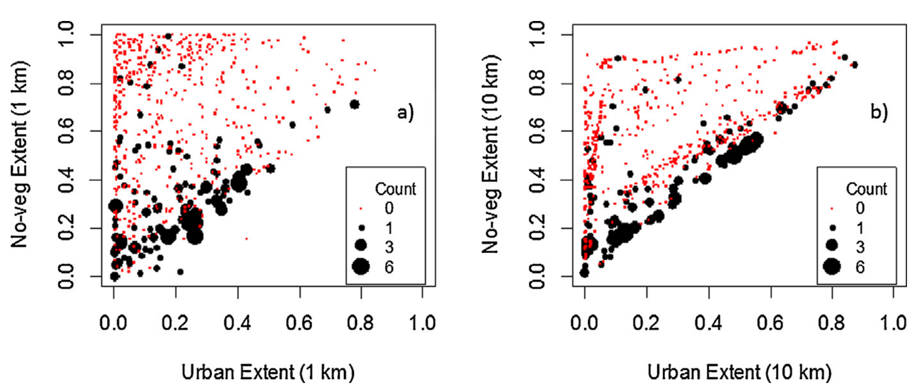

Fig. 3. The relationship between the extent of un-vegetated land, urban development and fire activity measured at 638 points on the Sydney WUI. (a) Scatter plot of the extent of urban land within 1 km of each point vs. extent of un-vegetated land within 1 km (both max = 1) with symbol size according to fire count (max = 6, and red = 0). (b) As (a) but at coarser scale (10 km).

Table 1
Variables used in the analysis. Fire count is the dependent variable.

	Description	Median (range)
Fire Count	Number of wildfires 1970–2008	0 (0–5)
Urban_1 km	% of Urban land within 1 km radius	0.155 (0.00–0.93)
Urban_10 km	% of Urban land within 10 km radius	0.177 (0.00–0.87)
No-veg_1 km	% of Un-vegetated land within 1 km radius	0.635 (0.00–1.00)
No-veg_10 km	% of Un-vegetated land within 10 km radius	0.577 (0.06–0.96)
No-veg Direction	Direction (degrees away from NW) to land with No-veg_1 km > 0.5	108 (0–180)
Elevation	Elevation from 30 m Digital Elevation Model	60 (0–1188)
Slope	In degrees, derived from DEM	3.76 (0–40.7)
Aspect	In quadrants (N, E, S, W)	29, 22, 22, 24%[a]
River Length	Length of watercourses (m) on 1:25,000 topographic maps within 250 m a.s.l.	2351 (0–6895)
Road Length	Length of roads on 1:25,000 topographic maps within 250 m a.s.l.	2939 (0–11,590)
Geology	Sandstone or Other. Derived from 1:250,000 geology map	40% Sandstone[a]
Vegetation	Most common vegetation within 1 km of the site (other than un-vegetated): Wet sclerophyll plus Heath, Dry sclerophyll, or Other (derived from Keith, 2004).	57% Wet[a] 34% Dry 9% Other
Neighbour count	Distance weighted mean fire count	As for fire count

[a] Percentage of sites in each class are shown rather than median and range.

Table 2
Correlation matrix among variables.

	Fire count	Urban_1 km	Urban_10 km	No-veg_1 km	No-veg_10 km	No-veg Dir.	Slope	Elevation	Aspect	River Length
Fire Count	1.000									
Urban_1 km	−0.007	1.000								
Urban_10 km	−0.016	0.570	1.000							
No-veg_1 km	−0.427	0.181	−0.030	1.000						
No-veg_10 km	−0.335	0.265	0.515	0.620	1.000					
No-veg Direction	0.058	0.041	0.115	−0.112	−0.069	1.000				
Slope	0.037	−0.265	−0.159	−0.064	−0.080	−0.026	1.000			
Elevation	0.056	−0.325	−0.274	−0.101	−0.174	−0.081	0.959	1.000		
Aspect	0.029	−0.269	−0.169	−0.052	−0.074	−0.032	0.993	0.954	1.000	
River Length	−0.077	−0.105	−0.183	0.031	−0.110	0.016	0.024	0.019	0.023	1.000
Road Length	−0.108	0.191	0.238	0.136	0.196	−0.038	0.058	0.028	0.062	−0.208

plots of urban vs. un-vegetated land extents revealed distinct relationships with Fire Count at both 1 km and 10 km radii (Fig. 3). In all of the plots there is a non-occupied zone where urban extent + un-vegetated land extent exceeds 1 (this cannot happen). The great majority of the fires occur near the line of equality where urban extent = un-vegetated land extent. Where un-vegetated land extent exceeds urban extent, fires are rare, particularly at 10 km radius.

The final model contained negative effects of un-vegetated land at 1 km and 10 km radii and a positive effect of urban land at 10 km radius. There was a negative interaction between No-veg_10 km and Urban_10 km such that where Urban_10 km is high, Fire Count is higher but responds more strongly to No-veg_10 km. There was also a positive effect of slope and a negative effect of River Length. (Table 3(a), Fig. 4). No-veg_10 km was the most important variable in the model, followed by Urban_10 km, No-veg_1 km and then the interaction. This model captured 44% of variation (pseudo-$r^2 = 0.445$). There were 12 supported alternative models, all involving the addition or removal of Slope, Clearing Direction, Road Length, Elevation. No-veg_1 km, No-veg_10 km, Urban_10 km and River Length were in all of these models. When the spatially lagged response variable (Neighbour Count) was included in the modelling process, River Length did not remain in the model, but all of the other terms did, with very similar estimates (slopes) to the final model (Table 3(b)). This model explained more variation than the final model (pseudo-$r^2 = 0.474$) but Neighbour Count was the most important variable in the model and the importance of all the other variables was reduced. Fire count was weakly but significantly spatially autocorrelated, and the addition of the Neighbour Count did not greatly reduce autocorrelation: Moran's I for final model residuals = 0.124 ($p < 0.0001$), with spatial lag $I = 0.111$ ($p < 0.001$). The final model had an accuracy of 85.2% in discriminating points with and without fires (using 0.2 to discriminate) in the validation sample (omission errors = 4%, commission errors = 56%). Neither vegetation type nor geology were selected in the models, presumably because they add little to the effects captured by the No-veg variables.

Fitting a zero-inflated Poisson model to the full data gave very similar predictions to the standard Poisson model with the subset of the data. However, the zero-inflated model explained less variation (captured 29.5% of deviance compared to 47.5%), and the interaction between No-veg_10 km and Urban_10 km was absent. The regression tree analysis identified primary, secondary and tertiary divisions among sites based on No-veg_1 km, No-veg_10 km and Urban_10 km, respectively (Fig. 5). The tree indicated that low Fire Count can be achieved by high levels of No-veg_1 km (mean 0.09), high Fire Count is likely with low levels of un-vegetated land at both 1 km and 10 km radius (mean 1.27), but the highest Fire Counts occur where there is low No-veg_1 km, intermediate No-veg_10 km (between 0.25 and 0.57) and high levels of Urban_10 km (>0.47). The mean number of fires in these sites was 4.33, almost 15 times higher than the overall mean.

4. Discussion

Syphard's studies (Syphard et al., 2007, 2009) have shown that fire activity follows a humped relationship with human population density in Mediterranean ecosystems across five continents, and concluded that this was due to the balance of the positive effect of people as igniters of fire and the negative effects of un-vegetated land at preventing fire. In this analysis, we have shown that this balance does occur and both population and un-vegetated land have a profound and countervailing influence on fire count in our study area. The countervailing effects of un-vegetated land and population is probably the reason that Archibald, Roy, van Wilgen, and

Table 3
Best model for fire count. Poisson error and log link ($n = 262$, pseudo-$r^2 = 0.422$). Relative importance is calculated as change in pseudo-r^2 when dropped from model. The sum is less than total pseudo-r^2 because of cross correlation.

	Estimate	Std. Error	*z* value	Pr(>|*z*|)	Relative importance
(a) Final model					
(Intercept)	0.991	0.276	3.588	0.000	
No-veg_10 km	−2.266	0.784	−2.889	0.004	0.054
Urban_10 km	5.250	1.225	4.286	0.000	0.048
No-veg_1 km	−1.901	0.496	−3.834	0.000	0.033
No-veg_10 km: Urban_10 km	−4.902	1.752	−2.798	0.005	0.018
River Length	−0.00016	0.00007	−2.327	0.020	0.012
Slope	0.011	0.007	1.503	0.133	0.005
(b) Including spatial lag					
(Intercept)	0.580	0.228	2.542	0.011	
Neighbour count	0.020	0.004	4.905	0.000	0.041
No-veg_10 km	−2.057	0.771	−2.667	0.008	0.019
Urban_10 km	3.674	1.332	2.758	0.006	0.030
No-veg_1 km	−1.869	0.495	−3.776	0.000	0.030
No-veg_10 km: Urban_10 km	−3.274	1.875	−1.746	0.081	0.006
Slope	0.011	0.007	1.492	0.136	0.004

Scholes (2009) found a negative relationship between population density and fire activity across southern Africa: the un-vegetated land effect outweighed the ignition effect.

Un-vegetated land and urbanization both affect fire activity at multiple scales. Un-vegetated land at 1 km had a strong influence on Fire Count, and this is because un-vegetated land at this scale directly inhibits fires from igniting and spreading in WUI. Thus, fuel treatments in or close to the WUI will provide the best reduction in fire frequency and consequent risk. This conclusion has been made by studies examining other aspects of fire activity (Bhandary & Muller, 2009; Price & Bradstock, 2010) and is reflected in policy around the world (RFS, 2006; Schoennagel, Nelson, Theobald, Carnwath, & Chapman, 2009). Un-vegetated land at 10 km also had a strong influence on Fire Count and this is probably because high levels of un-vegetated land at this scale protects areas from the spread of large fires.

Urbanization is predominantly a large-scale influence. Urban extent at 1 km had no effect on Fire Count, whereas urban extant at 10 km had a strong effect. There are probably two reasons for this scale effect. Firstly, people are relatively mobile and their day-to-day activities probably take them more than 1 km from their homes. For example, the average trip length for people in this region is 8.7 km (Anonymous, 2013). Secondly, since population density scales with the square of the radius, 100 times more people are involved at the 10 km radius than the 1 km radius so the pool of potential fire starters is much greater. Syphard et al. (2009) found a similar result that the hump in the fire vs. population relationship was more pronounced as the size of the area considered was

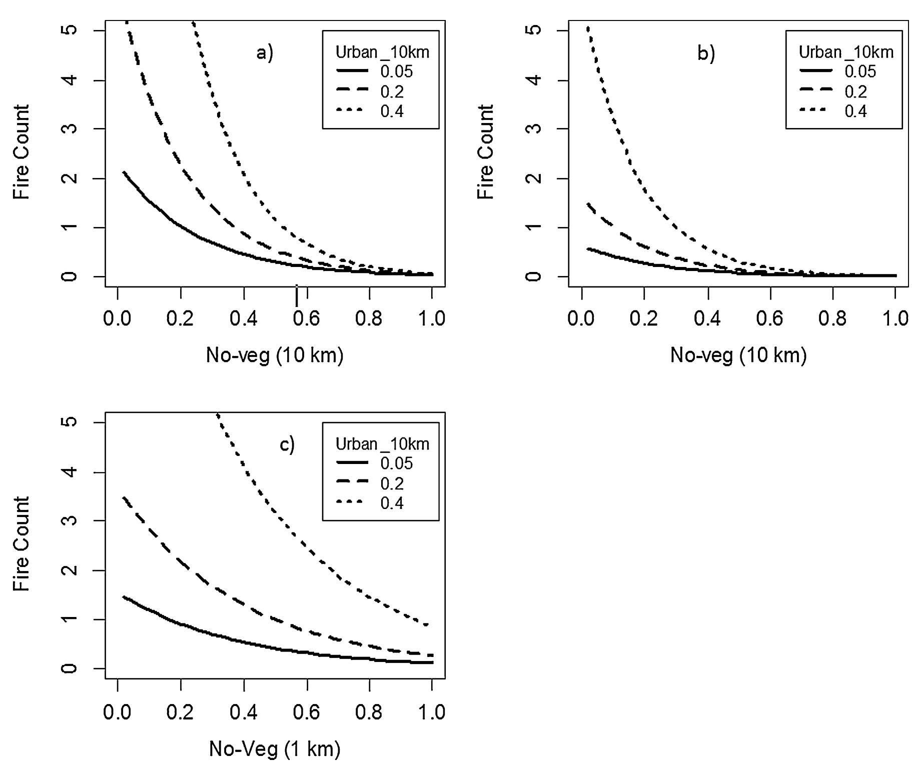

Fig. 4. Final model for fire count (in 38 years). (a) Against No-veg_100 km at different levels of Urban_10 km (proportion of urban land within 10 km radius) with No-veg 1 km held at 0; (b) as (a) but with No-veg_1 km held at 0.5; (c) against No-veg_1 km for km (the proportion of the vegetation within different levels of Urban_10 km) with No-veg_10 km held at 0.1. Other variables are held at their median levels.

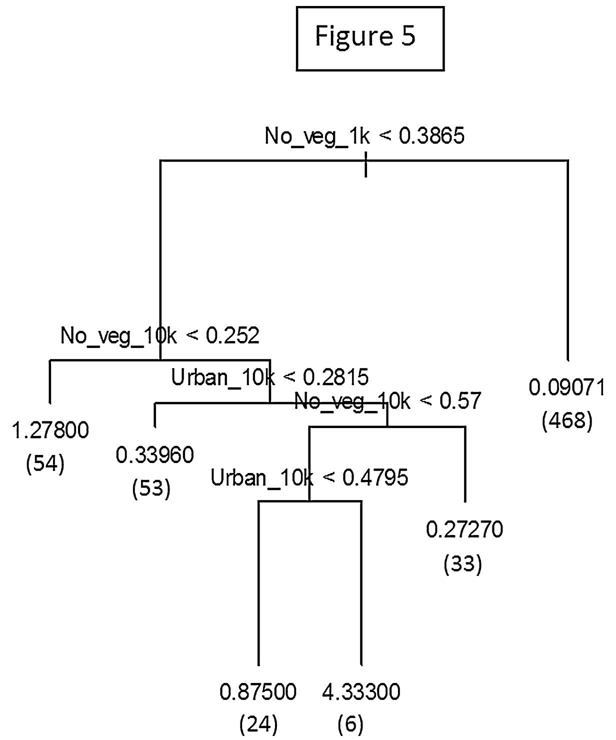

Fig. 5. Regression tree results. The numbers at each terminal node are the mean fire count for the node and the sample sizes are in parenthesis. Each division is a logical expression and the tree continues to the left for a positive and to the right for a negative response. For example, the left hand terminal node states that the mean fire count for sites with No-veg_1 km < 0.3865 and No-veg_10 km < 0.252 is 1.278.

increased. There have been previous studies relating fire activity to human settlement patterns (usually measured as road densities or distance to roads (Larjavaara, Kuuluvainen, Tanskanen, & Venalainen, 2004; Romero-Calcerrada et al., 2008; Vilar, Woolford, Martell, & Martin, 2010)), but, only Syphard et al. (2009) has considered the scale at which the population effect occurs, and none have identified the relative contribution of urbanization and un-vegetated land.

When we combine the multiple scales and the different type of effects of un-vegetated land and urbanization, we find that fire activity peaks in areas where urbanization has occurred but a large proportion of the native vegetation remains (Fig. 3). The effect is much stronger at larger scales. This appears to suggest that fires are most common where un-vegetated land in urban areas has been little other than to accommodate the houses. Only a small amount of additional un-vegetated land is required to greatly reduce the number of fires. Our results are consistent with our expectation that fire activity is likely to be highest in amenity-led forest communities and least in farming areas, with highly urbanized areas in between these extremes. To validate this conclusion, we intersected the sample points with a 1:50,000 land use map (New South Wales Office of Environment and Heritage, unpublished data) and found that points classified as farming (chiefly grazing) had a much lower mean Fire Count than those classified as rural residential or natural (0.083, $n = 157$ cf 0.558, $n = 217$, ANOVA $F = 27.34$, $p < 0.001$). Points classified as urban were lowest of all (0.063), though the sample was small ($n = 16$) and not significantly different to farming.

We had expected directionality to be important because major fires in this region are associated with a particular synoptic weather pattern with strong West or North-west winds (Cunningham, 1984). The lack of such a relationship may be because the majority of fires at the WUI are small and do not occur on those ‘blow up’ days or otherwise because the role of the westerly winds in fire spread decreases near the coast, where most of the WUI is situated. On the other hand, the study confirmed an effect of slope. Sloping land has higher Fire Count, which conforms to most studies of the effect of slope on fire, and is due to the combined effect that slopes promote fire spread (Catchpole, 2002) and also hinder fire management. Also, Fire Count was highest in dry sclerophyll forest and on sandstone geology. These two features are associated (they tend to occur together) and are common elements of the landscape. All other vegetation/geology combinations are more resistant to fire (e.g. moister forests or drainage lines).

Our results have several management implications. Most importantly we have found that urbanization had a strong positive effect on Fire Count and this must be because people are starting more fires near urban areas. It follows that programs that can successfully reduce ignition sources would have a large effect on fire risk. Un-vegetated land at the 1 km scale was also an important determinant of Fire Count. This implies that fuel treatments or other risk reduction measures near to the houses will be effective. Indeed, about 40% of wildfire ignitions in this region are within 2 km of the WUI (Price & Bradstock, 2013b). Researchers and policy makers have recognized the need to concentrate fuel treatment effort in the WUI (Schoennagel et al., 2009), though it is also realized that this is more expensive than treatments further from the WUI (Berry & Hesseln, 2004). Analysis of house loss patterns in the devastating 2009 Victorian fires, also suggests that vegetation extent at a distance of approximately 1 km is an important determinant of damage (Price & Bradstock, 2013a). However, other studies of house loss tend to highlight an even closer zone from 30 to 60 m (Bhandary & Muller, 2009; Cohen, 2001; Gibbons et al., 2012). We could not analyze Fire Count at such a fine scale because the mapping was not sufficiently accurate to locate houses and vegetation precisely enough.

Our results also confirm that urban planning can be used to reduce fire risk, as suggested via simulations by Syphard, Bar Massada, Butsic, and Keeley (2013). ‘Infill’ development where new suburbs are built between existing suburbs will result in fewer fires than ‘leapfrog’ development where new suburbs push further into the native vegetation. Infill development acts to maximize un-vegetated land at both 1 km and 10 km scales, compared to leapfrog development. Hence, infill both reduces ignitions and protects from fire spread.

Our study falls short of a comprehensive quantification of risk because fires vary in their degree of impact on human values. In particular, damaging fires usually occur on days when the weather is hot, dry and windy (Blanchi, Lucas, Leonard, & Finkele, 2010). It is possible that most of the smaller fires which are more frequent near to urban centres, occurred in more benign conditions and hence carried less inherent risk. Unfortunately we could only determine the weather conditions for fires post 2001, so weather could not be considered. Since prescribed fires are used to reduce the risk of subsequent wildfire (Fernandes & Botelho, 2003), it would have been useful to include the number of prescribed fires as a potential driver of wildfire patterns. However preliminary analysis suggested that prescribed fire was positively related to Fire Count (i.e. more wildfires in places with more prescribed fires). This is presumably because fire managers have been deliberately targeting their prescribed burns in areas that they know have high wildfire frequency. In light of this result, we decided not to include prescribed fire count in the main analysis.

Nevertheless, the study quantifies several spatial aspects of fire risk that have not been explicitly studied before. This approach can be used to produce a regional map fire risk that is more sophisticated than previous empirically derived attempts (Chen, 2005) and would be a useful complement to simulation approaches (Chuvieco et al., 2010; Keane et al., 2010). If used in conjunction with other analyses (such as models of ignition location and rate (Penman

et al., 2013)), it could form an important part of a comprehensive and empirically based risk assessment or map. Such a comprehensive risk assessment is a topic of current research at our centre.

5. Conclusions

In conclusion, this study has found countervailing effects of un-vegetated land and population on fire activity at multiple scales. Cities act both to promote ignitions and to prevent spread. The highest rates of fire activity are in relatively urbanized areas with little un-vegetated land (dense communities in the forest) and the least are in the opposite situation (farming land). The strongest reduction on fire occurrence will be obtained by reducing ignitions or fuel in the immediate vicinity of assets.

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