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Research article

The drivers of wildfire enlargement do not exhibit scale thresholds in southeastern Australian forests

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ABSTRACT

Wildfires are complex adaptive systems, and have been hypothesized to exhibit scale-dependent transitions in the drivers of fire spread. Among other things, this makes the prediction of final fire size from conditions at the ignition difficult. We test this hypothesis by conducting a multi-scale statistical modelling of the factors determining whether fires reached 10 ha, then 100 ha then 1000 ha and the final size of fires >1000 ha. At each stage, the predictors were measures of weather, fuels, topography and fire suppression. The objectives were to identify differences among the models indicative of scale transitions, assess the accuracy of the multi-step method for predicting fire size (compared to predicting final size from initial conditions) and to quantify the importance of the predictors. The data were 1116 fires that occurred in the eucalypt forests of New South Wales between 1985 and 2010.

The models were similar at the different scales, though there were subtle differences. For example, the presence of roads affected whether fires reached 10 ha but not larger scales. Weather was the most important predictor overall, though fuel load, topography and ease of suppression all showed effects. Overall, there was no evidence that fires have scale-dependent transitions in behaviour. The models had a predictive accuracy of 73%, 66%, 72% and 53% accuracy at 10 ha, 100 ha, 1000 ha and final size scales. When these steps were combined, the overall accuracy for predicting the size of fires was 62%, while the accuracy of the one step model was only 20%. Thus, the multi-scale approach was an improvement on the single scale approach, even though the predictive accuracy was probably insufficient for use as an operational tool. The analysis has also provided further evidence of the important role of weather, compared to fuel, suppression and topography in driving fire behaviour.

1. Introduction

Wildfires are complex phenomena, which makes it difficult to accurately predict their behaviour and therefore plan effective mitigation. One of the main complexities is size and scale: For example, small fires may be easier to extinguish than large ones because their perimeters are relatively small and the conditions on the fire-ground (e.g. terrain, vegetation and weather) may be inherently more homogeneous. Large fires may transcend large variations in environmental conditions across time and space, making their development more complex and difficult to predict. Given that large fire are responsible for the major impacts on ecological and human values, an understanding of the way in which small fires have the potential to develop into large, complex wildfires is required to improve our ability to predict and mitigate impacts.

The drivers of fire behaviour across different scales of wildfire size are poorly understood. Several studies have suggested that there are scale-related thresholds or breakpoints in fire behaviour which reflect changes in the main drivers of fire behaviour and which require different management to counter that behaviour (Boer et al., 2008; Liu et al., 2013; O'Donnell et al., 2014; Peters et al., 2004; Ricotta et al., 2001; Slocum et al., 2010). Much of the evidence comes from identifying distinct phases in the frequency distribution of fire size (Boer et al., 2008; McKenzie and Kennedy, 2012; O'Donnell et al., 2014; Pueyo, 2007; Ricotta et al., 2001).

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Peters et al. (2004) defined four thresholds for a fire: initiation, spread within a fuel patch, among fuel patches and 'blow-up' that demarcate major shifts in the drivers of fire behaviour. In particular, the 'blow-up' stage represents a transition whereby feedback from the fire's energy cause pyro-cumulus clouds and strong local winds (Cruz et al., 2012; McRae et al., 2013; Peters et al., 2004). If these thresholds and the main drivers of fire behaviour at each scale could be quantified, then fire size could be predicted more accurately and appropriate management could be more effectively targeted. Empirical tests of these thresholds are rare. Slocum et al. (2010) analysed 142 fires in Florida pine savannah at different scales, and found that wind speed was the most important driver for small fires but soil moisture was more important for large fires. Liu et al. (2013) found that for 146 fires in Boreal China, fuel and topography were most important in determining the final size of small fires, but weather was more important for larger fires. O'Donnell et al. (2014) compared the selectivity of different vegetation types among 60 small and large fires and concluded that large fires occur when wet years drive fuel growth in woodlands that normally do not have sufficient fuel connectivity to burn.

Here, we used the Peters et al. (2004) concept of fire-stages to develop independent statistical models of the growth of fire size at four stages to capture changes in processes and scale as fires grow, for a large sample of fires (>1000). We used fire size data based on historical fire mapping from New South Wales (NSW), Australia, and a range of weather, fuel, topographic and suppression variables as candidate predictors, selecting variables that have been shown to influence various aspects of fire behaviour such as size, spread, severity (Bradstock et al., 2009; Price et al., 2015; Price and Bradstock, 2012; Thompson et al., 2007). Rather than examining fire size distributions (Boer et al., 2008; Slocum et al., 2010) or splitting the sample of fires into size classes (Liu et al., 2013), each fire was treated as an independent sample point at each scale. Hence, the four stages reflected a series of statistical questions: i) for all fires, what determined whether each fire reached 10 ha in size? ii) for those that reached at least 10 ha, what determined whether each reached 100 ha? iii) for those that reached 100 ha what determined whether each reached 1000 ha? iv) and for those that reached 1000 ha, what determined the final size? At each stage, the physical environment was measured in polygons large enough to encompass each fire and its perimeter and the weather was measured over a time-frame related to average time it takes for fires to reach that size threshold.

The main objective of the study was to gather evidence of scale-thresholds defining different determinants of fire spread (as hypothesized by Peters et al. (2004)). Secondary objectives were to evaluate whether a multi-stage approach yielded more accurate prediction of fire size than a single-step approach (based on conditions at ignition), and to compare the relative importance of the drivers (fuels, weather, topography and suppression) at different scales. In line with the threshold hypothesis, we predicted that the main drivers of fire spread would change across the scales.

2. Methods

2.1. Study area

The study was confined to forested vegetation dominated mainly by *Eucalyptus* spp. in NSW (Fig. 1). These form a band along the mountains and adjacent coast throughout the state and range in climate from temperate to moist sub-tropical. The dominant vegetation in these areas is either dry or wet sclerophyll forest, though there are pockets of rainforest, grassy woodland and heath (Keith, 2004). The extent of vegetation clearing was variable but 80% of the fires used had less than 20% of the forest within 200 m of the ignition point cleared and replaced with non-vegetated surfaces or non-native vegetation.

2.2. Data

Fire history mapping (perimeters) from 1985 to 2010 was obtained from the two major fire management agencies, the NSW Rural Fire Service and NSW Office of Environment and Heritage (unpublished data). From these data, we identified two overlapping subsets of data: 1) all fires where the ignition point and start date was known (n = 1116). The precise location of ignition points was necessary for small scale analysis (up to 100 ha scale). 2) Those fires >100 ha with known start and end date but not necessarily with known ignition point (n = 720). The sample was only 4% of all mapped fires from the period and over-represented fires of about 1 ha size and more recent fires and under-represented fires of about 100 ha (Fig. 2). However, the statistical method was robust to these slight biases. For these fires, knowledge of their duration was necessary to estimate weather conditions throughout the fire, while ignition location was less important because predictor values were averaged over larger areas. Instead we used the polygon centroid. Of the fires with known ignition point and date, 78.5% were smaller than 10 ha, 13.9% were between 10 and 100 ha, 11.1% were between 100 and 1000 ha. Only 6.3% (64 fires) were larger than 1000 ha but these accounted for more than 95% of the total area burnt.

The fire history mapping was also used to generate a time-since fire layer for each year, and this was also used in conjunction with the regional vegetation map (Keith, 2004) and published fuel accumulation equations (Watson, 2011) to estimate fuel loads across the study region for each year. Areas mapped as having no native vegetation were assumed to have no fuel, though in reality, many would have included pasture or cropping land with a low fuel load. A disruption layer was created by creating a grid of disruption widths (the sum of the widths of all roads railways and watercourses crossing each cell) according to the Australian Standard for widths (AS2482-1989) (source: Rural Fire Service NSW, unpublished data). The widths varied from 5 m for tracks and dry creeks to 60 m for freeways.

Gridded daily weather data were obtained by downscaling to a 10 km resolution the outputs of World Climate Research Program's (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel dataset (Clarke et al., 2011). These modelled variables consisted of daily values of FFDI, wind maximum speed (and direction), minimum relative humidity, maximum temperature, rainfall and drought factor. These values correlated closely with weather station data for the same period (H. Clarke, pers. Comm). We also calculated the same values from observations at the closest weather station to each ignition point (Bureau of Meteorology, unpublished data). The modelled weather data were used in preference to the actual station observations because they performed better in the statistical modelling, probably because many of the fires occurred at considerable distances from the nearest station (13% of ignitions were >50 km from a station).

Fire suppression can affect fire size, most strongly in the early growth stages (Arienti et al., 2006; Plucinski, 2012) and particularly for grass fires (Plucinski, 2013). There were no records of suppression effort for fires used in this study. Instead, we used two variables as surrogates of suppression effort. A grid of distance to the nearest road was created from 1:25,000 digital roads data, which included major fire trails (source: Rural Fire Service NSW, unpublished data). The speed of the response and the suppression effort are greater when road access is close (Arienti et al., 2006). A spatial layer of towns from 1:250:000 topographic maps (from Geoscience Australia, www.ga.gov.au) was used to create a grid of