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Research article

Suppression resource decisions are the dominant influence on containment of Australian forest and grass fires

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ABSTRACT

Fire agencies aim to contain wildfires before they impact on life, property and infrastructure and to reduce the risk of damage to the environment. Despite the large cost of suppression, there are few data on the success of suppression efforts under varying weather, fuel and resource scenarios. We examined over 2200 forest and 4600 grass fires in New South Wales, Australia to determine the dominant influences on the containment of wildfires. A random forest modelling approach was used to analyse the effect of a range of human and environmental factors. The number of suppression resources per area of fire were the dominant influence on the containment of both forest and grass fires. As fire weather conditions worsened the probability of containment decreased across all fires and as fuel loads and slope increased the probability of containment decreased for forest fires. Environmental controls limit the effectiveness of wildfire management. However, results suggest investment in suppression resources and strategic fuel management will increase the probability of containment.

1. Introduction

Wildfires have caused significant loss of human lives and property and billions of dollars of economic losses across the globe (Gill et al., 2013). For example, destructive wildfires reported in the media in 2017 occurred in Spain, Portugal, South Africa, USA, Canada, Chile, New Zealand and Australia. The cost of impact can be reduced through fire management actions. Fire agencies deploy resources to suppress wildfires to protect life, property and infrastructure from impact by fire and reduce the risk of damage to the environment. Active suppression of fires can reduce the total area burnt (Cumming, 2005; DeWilde and Chapin, 2006) however, fires that escape initial attack can become large and costly to manage (Calkin et al., 2013; Gebert and Black, 2012). Therefore, it is important to know what factors influence the probability of containment of fires.

Environmental factors can have a strong influence on the probability of containment. Fuel type (Arienti et al., 2006; Hirsch et al., 2004), fuel load (McCarthy et al., 2012; Plucinski, 2012), weather conditions (Arienti et al., 2006; Plucinski, 2012, 2013) and slope (McCarthy et al., 2012) may influence the probability of containment. These factors are likely to be important because they all influence various aspects of fire behaviour - rate of spread, flame height, intensity and likelihood of spotting (Cruz et al., 2015). All these factors can influence fire containment difficulty. The faster a fire spreads, the larger its perimeter grows, requiring crews to establish a longer length of control line to contain the fire compared with a slower spreading fire (e.g. Parks, 1964; Weber et al., 2009). The higher the fire's intensity, the higher the flame height, the more likely spot fires will occur, and the less likely ground crews can extinguish the fire directly at the fire edge. The upper limit for direct attack of fires with hand tools is estimated to be 500 kW/m and for ground-based crews around 2000–4000 kW/m (Hirsch and Martell, 1996). Fire intensity also influences the rate of control line construction. For example, Loane and Gould (1986) found a machine crew (D6 dozer with tankers and 9 firefighters) constructed a control line at a maximum and constant rate up to 500 kW/m but this rate drops sharply to zero for intensities above 2000 kW/m. They found a similar pattern for hand crews with control line construction occurring at a constant rate until falling sharply to zero for intensities above 800 kW/m.

Decisions around suppression response are also known to influence the probability of containment. One of the key decisions is resource placement as resource response time (Arienti et al., 2006; Plucinski, 2012) and fire area when crews arrive at the fire (Arienti et al., 2006; McCarthy et al., 2012; Plucinski, 2012, 2013) can influence the probability of containment. A fast response time will lead to a smaller fire area when crews begin suppression operations which could be important when a fire is spreading rapidly. However, under conditions conducive to a low rate of spread, response time would be less

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influential as the fire size will change little over time. Another key decision is the number and type of resources to deploy to the fire as this relates to the rate of control line construction (Fried and Gilless, 1989; McCarthy et al., 2003). More resources can create a control line faster and for successful containment to occur the rate of construction needs to exceed the rate of fire perimeter growth (Weber et al., 2009).

There are few studies globally that have quantified the influence of various environmental and human factors on the probability of suppression. In Australia, existing studies have used limited datasets. These studies have considered suppression success in either forest (McCarthy et al., 2012; Plucinski, 2012) or grass (Plucinski, 2013) fires but have used a maximum of 334 fires. We aimed to conduct a comprehensive assessment of the factors affecting containment using a much larger data set (n = 6837) and a broader range of factors than has previously been attempted. No comprehensive data that contains all relevant factors was available, so we used data that is consistently available from fire incident reports plus weather, fuel load and topographic data. Specifically, we asked what is the relative importance of environmental and human factors in containing grass and forest fires at various time periods from when the first ground crews arrived at the fire. From the findings of previous studies, we hypothesise that:

1. Factors which influence fire behaviour – fuel, weather and topography - will be important in determining the probability of containment.
2. The number of resources and the response time will be important in determining the probability of containment.

2. Materials and methods

The study area was the state of New South Wales in Australia. The population is largely city based with over 60% of the population residing in the greater Sydney area (http://www.censusdata.abs.gov.au, accessed April 2017). Other high population centres are along the coastal fringe and nearby inland areas. Large areas of western New South Wales are sparsely populated (Collins et al., 2015). The natural vegetation of the study area (Fig. 1) is varied with *Eucalyptus* spp. dominant forests and woodlands in the coastal and mountainous hinterland areas (Keith, 2004). The climate in these areas ranges from temperate to moist subtropical and these forests can burn at very high intensities (Murphy et al., 2013). The dominant species in the semiarid woodlands in central and western New South Wales are *Eucalyptus, Casuarina, Acacia* and *Callitris* spp. (Keith, 2004). These woodlands burn infrequently at low to medium intensities (Murphy et al., 2013). Chenopod shrublands dominate the arid and semiarid regions of western New South Wales where rainfall or local soil moisture is too low to support tree-dominated vegetation (Keith, 2004). Chenopods typically burn as low intensity fires although fires are rare events (Murphy et al., 2013). The grasslands are predominately perennial tussock grasses (Keith, 2004) which burn as low intensity fires (Murphy et al., 2013). Agriculture areas cleared of natural vegetation are largely pasture and croplands which burn infrequently as low intensity grass fires (Murphy et al., 2013).

Fire and response data were taken from fire incident records held by the New South Wales Rural Fire Service who are responsible for the suppression of wildfires across approximately 95% of New South Wales, Australia. Only incident records contained in both the fire incident reporting system and incident management system were included in the study as both sets of data were used to confirm the reported information. Incidents where the time the first ground crews arrived at the fire was listed as 0 were removed as this is a default value for the incident reporting system i.e. the recorder may have failed to enter the actual value. Incidents where no tankers were tasked to the fire or where the fire incident report stated that ground crews delayed attacking the fire as the fire was either inaccessible or was not posing a threat to property were also removed. The study data included incident and response records from July 2005 to June 2013.

Predictor variables used in the study are defined in Table 1. The time the fire was contained was defined as the time when the fire is no longer spreading i.e. when the final fire area was reached. The response time refers only to when the first ground crews arrived at the fire. The peak number of firefighters and tankers at the incident was used as this is the only field available in the fire incident reporting system on the number of resources at the fire and the incident management system does not record the arrival and departure times of all resources over the duration of the fire. All firefighters and tankers tasked to the fire were assumed to be attempting to contain the fire as it was not possible to ascertain if some of these resources were used for other purposes such as property protection. Size/category of tankers, earth-moving machinery and aircraft despatched to the fire was not available. Earth-moving machinery only used to strengthen containment lines after the fire had been contained or to remove dangerous trees were not recorded as assisting in containing the fire. Aircraft only used to map the fire or to provide reconnaissance were not recorded as suppressing the fire. For analysis purposes, the peak number of tankers and firefighters were divided by the square root of the final fire area. This was done to enable comparison between fires and to scale the resources to the length of perimeter needing containment. The number of earth-moving machinery and aircraft used was converted to a binary factor as these resources were not used at every fire. Earth-moving machinery was used on 5% of grass fires and 24% of forest fires and aircraft used on 4% of grass fires and 27% of forest fires. Broad fuel type was either a grass or forest fire. Crop fires were included in grass fires and those classified as scrub or bush fires were included as forest fires.

The ignition cause was assigned to one of five cause types: deliberate, lightning, powerline, accidental and undetermined. Deliberate ignitions included arson and fires where it was suspected that they were intentionally lit. Powerline ignitions were due to fires starting because of powerlines clashing, arcing or vegetation or animals contacting the live parts of the network or breakage of wires, poles or other parts of the network. Accidental ignitions included all other human caused fires that were unintentionally started e.g. escapes from prescribed burns, camping or cooking fires, fires caused by equipment or machinery use or smoking. Undetermined cause fires included all fires where the fire cause was unknown or unreported.

The fuel load at the ignition point was estimated for forest fires using fire history databases (NSW Government unpublished data) to delineate the time since fire, the vegetation class based on Keith (2004) using vegetation data (Vegetation Classes of NSW ver. 3.03, http://data.environment.nsw.gov.au/dataset/vegetation-classes-of-nsw-version-3-03-200m-raster-david-a-keith-and-christopher-c-simpc0917, accessed April 2017) and fuel accumulation relationships (Gordon and Price, 2015; Watson et al., 2012). The grassland and forest fire danger indices combine ambient weather variables (temperature, relative humidity and wind speed) and fuel moisture (% curing for grass and drought factor for forest) to derive an index of the forward rate of spread and suppression difficulty of fires (Noble et al., 1980). For grass fires, the grassland fire danger index was calculated using 100% grass curing as there were no grass curing data available for the study.

Random forests were used to analyse the factors which influence the containment of fires (Breiman, 2001). Random forests are an ensemble learning technique, a random subset of the predictor variables are used to develop individual classification trees that are assigned a class vote, and then the predictions from all trees are combined using majority vote (Breiman, 2001). The model error is calculated by comparing the prediction of each tree with data held back during its development (out of bag samples) and then averaged over all observations (Cutler et al., 2007). Variable importance for a given variable is estimated by comparing increases in out of bag error when that variable is randomly permuted while all others remain unchanged (Cutler et al., 2007). Partial dependence plots provide a graphical representation of the marginal effect of a variable on the response and are developed for an