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Determinants of the occurrence of unburnt forest patches: Potential biotic refuges within a large, intense wildfire in south-eastern Australia

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ABSTRACT

Large, intense fires are generators of heterogeneity in many ecosystems. An important component of this heterogeneity is the occurrence of unburnt patches within the fire boundary: these fulfil a number of ecological functions including serving as refuges for fire-sensitive organisms. An important issue for land managers is the degree to which potential refuges occur 'naturally' versus occurring as a result of interventions such as planned burning. Here, we examine the factors contributing to the occurrence of unburnt patches within the Kilmore–Murrindindi fire complex, a severe wildfire that encompassed ~250,000 ha and resulted in 159 human fatalities in Victoria, Australia, in 2009. Though an extreme event, this fire is representative of large, intense fires that periodically occur in south-eastern Australia. Unburnt patches $\geqslant 1$ ha occupied less than 1% of the area within the fire boundary, with mean size of 27.1 ha (range 1–306 ha). Overall, the probability of points within the fire boundary remaining unburnt was most strongly influenced by topographic position, vegetation type and fire intensity in the surrounding area. In dry eucalypt forest, time since fire (a surrogate for fuel structure) was also important. The influence of all factors was strongly contingent on prevailing weather during the fire, with no unburnt patches occurring in extreme fire conditions. In this fire, most unburnt patches arose 'naturally' due to microclimatic effects of topography and vegetation. While fuel reduction burning has the potential to create unburnt patches in some circumstances, these are likely to exhibit simpler vegetation structure than those arising due to microclimate. Potential refuges in the form of unburnt patches are more likely to arise in landscapes with greater topographic and vegetational variation. Conversely, in more uniform environments, fuel load and/or continuity are likely to have a greater influence on the occurrence of unburnt patches. Understanding these relationships will assist fire managers in directing resources at producing ecological outcomes that are less likely to arise without intervention.

1. Introduction

Fire is an important shaper of ecosystems, affecting the distribution of organisms across scales from the local to the global (Bowman et al., 2009). Fire regimes vary widely across ecosystems: however, globally, a number of systems are characterised by periodic, large intense fires (e.g. Turner et al., 2003; Fernandes and Rigolot, 2007; Bradstock, 2008; Veblen et al., 2008; Keeley and Zedler, 2009). Systems prone to large, intense fires are generally relatively productive, such that there is usually high vegetation biomass present, but most of this potential fuel is too moist to burn except under extreme weather conditions or after prolonged drought (Boer et al., 2008; Flannigan et al., 2009a; Bradstock, 2010). Global climate change models predict warmer, drier conditions in coming decades in a number of regions prone to large, intense fires (Flannigan et al., 2009b), which in turn may increase the size, frequency and intensity of these events (Piñol et al., 1998; Westerling et al., 2011; Cary et al., 2012).

Large fires are perceived to produce a homogenous and therefore biologically depauperate landscape (Bradstock et al., 2005; Burrows, 2008). This idea rests on the assumption that fire intensity is uniform throughout the affected area. However, there is a growing body of work indicating that variation in terrain, vegetation and weather leads to variation in fire behaviour, in turn resulting in a variegated pattern of burn severity (Turner et al., 1997; Broncano and Retana, 2004; Alexander et al., 2006; Hammill and Bradstock, 2006; Holden and Jolly, 2011). Variation in patterns of burn severity is an important source of landscape heterogeneity in fire-prone ecosystems (Turner et al., 2003; Burton et al., 2008; Schoennagel et al., 2008; Mori and Lertzman, 2011).

An important component of post-fire heterogeneity is the occurrence of unburnt patches within the fire boundary (DeLong and Kessler, 2000; Román-Cuesta et al., 2009; Robinson et al., 2013).

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These patches may act as refuges in which animals and fire-intolerant plants can escape the fire, and survive in and subsequently recolonise the post-fire landscape. While unburnt patches may arise due to stochastic variation in fire behaviour, they occur most predictably at sites that have lower flammability than their surrounds (Bradstock et al., 2005). This may be due to differences in fuel structure (e.g. fuel load, fuel density), lower fuel continuity, or higher fuel moisture (Catchpole, 2002). Low fuel loads and/or continuity may be the result of naturally sparse vegetation (e.g. rocky outcrops; Clarke, 2002) or due to fuel reduction by prior fire (Burrows, 2008), mechanical removal (Waldrop et al., 2010) or herbivory (Leonard et al., 2010). Elevated levels of fuel moisture are likely to occur in situations that are topographically protected from sun and wind (Wood et al., 2011) or where the vegetation itself contributes to creating a moist microclimate (Jackson, 1968; Bowman, 2000).

A number of studies have investigated the factors contributing to variation in fire severity (Chafer et al., 2004; Alexander et al., 2006; Bradstock et al., 2010; Price and Bradstock, 2012). Generally, fire severity has been found to be strongly related to prevailing weather conditions. Microclimate and fuel loads also affect fire severity and tend to become more influential as weather conditions and fire behaviour moderate. A focus on fire severity in previous studies is partly a product of severity being related to fire intensity (Keeley, 2009), which is a key determinant of whether fires can be successfully controlled (Catchpole, 2002). In addition, spatial patterns in fire severity are an important driver of post-fire ecological processes (Turner et al., 1998). Unburnt patches within a fire-affected area represent one end of the fire severity spectrum, but the occurrence of these patches is less well studied (Román-Cuesta et al., 2009). Several studies have examined spatial attributes of unburnt patches within wildfires in boreal forest, including noting associations of patches with particular landscape features (e.g. DeLong and Tanner, 1996; Burton et al., 2008; Perera et al., 2009; Madoui et al., 2010; Andison, 2012). However, few studies have systematically analysed the relative influence of multiple biotic and abiotic factors on the occurrence unburnt patches (but see Román-Cuesta et al., 2009). In addition, most studies on the occurence of unburnt patches have been focussed on conifer-dominated boreal forests. Investigations in non conifer-dominated temperate systems are rare.

The aim of this study is to identify the factors that contributed to the occurrence of unburnt patches within a major wildfire in a eucalypt forest-dominated landscape in south-eastern Australia, one of the most fire-prone ecosystems in the world (Pyne, 1992). This system exhibits complex topography, variation in fire history and flammability gradients across vegetation types (Gill, 2012). We test the hypotheses that the occurrence of unburnt patches is influenced by: (i) variation in fuel moisture related to microclimatic effects of topography and vegetation and (ii) variation in fuel load related to past disturbance. An underlying question that we address is the degree to which potential biotic refuges, in the form of unburnt patches, may arise due to human intervention, in particular planned burning, versus their 'natural' occurrence due to attributes of the landscape. The answer to this question has important implications for ecological fire management in fire-prone landscapes.

2. Methods

2.1. Study area and fire history

The study focused on the area affected by the Kilmore East–Murrindindi fire complex in 2009. This area extends over approximately 250,000 ha of Victoria, Australia (study area location: 37°28′S, 145°29′E). This fire complex resulted in the deaths of 159 people and destroyed over 1700 houses (Teague et al., 2010). The fires started on 7th February 2009 in conditions of extremely low humidity (<10%), high temperatures (>40 °C) and strong winds (gusts up to 70 km h^{-1}; see Cruz et al., 2012 for a detailed account of fire conditions and behaviour during the Kilmore East fire). The ignition of the fires was preceded by several years of drought and several weeks of hot (daily maximum temperatures >35 °C) weather. These climatic and weather conditions are typical of those in which large, intense wildfires occur in south-eastern Australia (Sullivan et al., 2012). The fires developed from two separate ignitions and subsequently joined to form the fire complex (Fig. 1). For the first few hours after ignition the fires moved in a south-easterly direction under the influence of north-westerly winds. On the evening of 7th February, a strong, gusty south-westerly wind change caused the fires to move towards the east-north-east on a wide front.

Fire severity for this fire complex was mapped by the Department of Environment and Sustainability (DSE) on the basis of differenced Normalised Burn Ratio derived from SPOT satellite data (DSE, 2009; Fig. 2). Fire severity was classified using a five-class scale reflecting the degree of damage to the vegetation caused by the fire (in descending order of severity: crown burn, crown scorch, moderate crown scorch, understorey burnt, unburnt). Measures of fire severity of this kind are closely correlated with fire intensity (Keeley, 2009). The pattern of fire severity indicates that the fires burned at high intensity (up to 90,000 kW m^{-1}; Cruz et al., 2012) before and immediately after the wind change. During this period the fires moved very rapidly (up to 153 m min^{-1}), due to high wind speeds and extensive spotting.

In these conditions the potential for fire suppression was extremely limited and control measures were focussed on localised attempts to protect human lives and assets (Teague et al., 2010). The Kilmore East and Murrindindi fires burnt approximately 75% and 50% of their respective final areas within 12 h of ignition. Most of the final boundary of the fire complex occurred where the fires moved out of forested country into cleared agricultural land, where low fuel loads caused self-extinguishment or allowed successful suppression. Towards the eastern edge of the fire complex, fires continued to burn in rugged country, mostly at low intensity, for several weeks.

Periodic large, intense wildfires are a feature of the eucalypt forests of south-eastern Australia (Pyne, 1992). Gill and Catling, 2002).

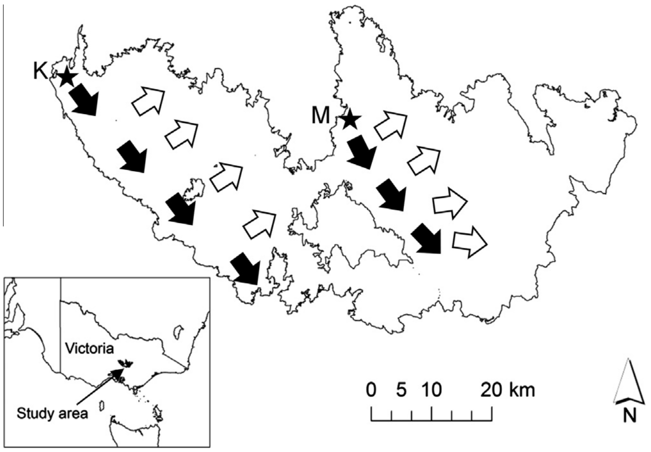

Fig. 1. Study area location and the movement and final boundary of the Kilmore East–Murrindindi fire complex. Stars indicate origins of fires (K = Kilmore East, M = Murrindindi). Solid arrows indicate fire movement before a south-westerly wind change on the evening of 7th February, hollow arrows indicate movement after the change.