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# Effects of fire severity and burn patchiness on hillslope-scale surface runoff, erosion and hydrologic connectivity in a prescribed burn

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ABSTRACT

Fire severity and burn patchiness are frequently cited as important to post-fire surface runoff and erosion, yet few studies quantify their effects. A better understanding of their role is needed to predict post-fire erosion and design prescribed burns. Therefore, this study quantified the effects of fire severity and burn patchiness on surface runoff, erosion and hydrologic connectivity using 116 unbounded runoff samplers. The samplers were installed in recently prescribed burnt dry eucalypt forest in Victoria, Australia. Sediment loads over 16-months were approximately three orders of magnitude higher on burnt compared with unburnt hillslopes while differences in runoff and erosion between the low and high severity hillslopes were relatively small. Unburnt patches were often highly effective at reducing hydrologic connectivity from upslope burnt areas, with sediment loads over 16-months reduced by 1.3%, 98.1% and 99.9% downslope of 1, 5 and 10 m wide unburnt patches respectively. Hydrologic connectivity was limited most effectively by wider unburnt patches (10 m) and during lower magnitude storms. The results suggest overall that post-fire runoff and erosion may be substantially limited by unburnt patches while fire severity is a less important factor (within the context of prescribed burning). Consequently, post-fire erosion models should consider the spatial arrangement of unburnt patches, and unburnt patches (>10 m wide) should be retained within prescribed burns to minimise erosion.

## 1. Introduction

Fire increases the susceptibility of landscapes to surface runoff and erosion by reducing vegetative cover, changing soil hydrologic properties and providing a readily erodible layer of sediment and ash (as reviewed by Certini, 2005; Neary et al., 1999; Shakesby and Doerr, 2006; Shakesby et al., 2000, 2007; Wondzell and King, 2003). As a result, hillslope erosion rates and concentrations of suspended sediments, nutrients and other constituents in streams may be much higher after fire (Neary et al., 2008; Smith et al., 2011b). Elevated constituent concentrations in streams may pose problems for aquatic ecology (Lyon and O'Connor, 2008; Minshall, 2003), water supply for domestic and agricultural purposes (Smith et al., 2011b), recreation and aesthetics (Smith et al., 2011a,b). For example, domestic water supply was disrupted following the 2003 and 2006/07 wildfires in south-eastern Australia resulting in boil water notices, water restrictions, water carting and the costly installation of new water treatment facilities for some towns (Smith et al., 2011b). Following a high severity fire in Yellowstone National Park in 1988 aquatic macroinvertebrate richness, total density and composition fluctuated for the duration of a 10 year study rather than reaching a constant equilibrium (as seen in a nearby reference stream) (Minshall et al., 2001). In addition to water quality impacts, high magnitude erosion (e.g. debris flows) in burnt areas pose a threat to property and human safety (Cannon et al., 2010).

The magnitude of erosion and water quality impacts following fire is highly variable and likely to depend on a number of factors. Those factors include the post-fire climatic conditions, terrain (slope gradient, aspect, geology and soil type), rates of vegetation recovery and characteristics of the fire regime (Cawson et al., 2012; Prosser and Williams, 1998; Shakesby and Doerr, 2006; Shakesby et al., 2000, 2007; Smith et al., 2011b). Two characteristics of the fire regime, fire severity and burn patchiness, are the focus of this study. Understanding their effects is important for developing post-fire erosion models and designing prescribed burns with minimal impact on runoff, erosion and water quality. Prescribed burns are fires that are deliberately lit to achieve management objectives (Graham et al., 2010; Tolhurst and Cheney, 1999). Their severity and patchiness can be manipulated by land managers through ignition patterns and the choice of weather and fuel conditions. Therefore, a better understanding of how fire

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severity and burn patchiness affect post-fire runoff and erosion could be used to achieve lower impact burns.

Fire severity (otherwise known as burn severity) is a measure of the loss of above and below ground organic matter caused by fire (Keeley, 2009). It is considered an important factor affecting post-fire runoff and erosion (Ferreira et al., 2008; Neary et al., 1999; Shakesby and Doerr, 2006). Yet, relative to the complexity of its effects (i.e. the large number of complicating factors – climate, soils, geology, vegetation, etc.), there are few studies that compare the runoff and erosion characteristics of different fire severities (as highlighted by Cawson et al., 2012). Its effects on post-fire runoff and erosion are thought to depend on the amount of soil heating during the burn (Doerr et al., 2006; Neary et al., 1999), and the loss of vegetative cover (Benavides-Solorio and MacDonald, 2005). Soil heating may affect runoff and erosion rates by affecting soil water repellency (DeBano, 2000; DeBano and Neary, 2008; Doerr et al., 2000; Letey, 2001), ash properties (Bodí et al., 2012; Larsen et al., 2009; Woods and Balfour, 2010), soil organic matter (Certini, 2005; Neary et al., 1999), critical shear stress (Moody et al., 2005) and aggregate stability (Blake et al., 2009). Vegetation cover reduces runoff and erosion by intercepting rainfall, protecting the soil surface and creating surface roughness (as reviewed by Cawson et al., 2012). Overall, less runoff and erosion are reported for low severity areas (Benavides-Solorio and MacDonald, 2005; Dragovich and Morris, 2002; Robichaud, 2000), or at least low fire severities are associated with post-burn soil properties less conducive to runoff and erosion (Doerr et al., 2006; Woods et al., 2007).

Wildfires and prescribed burns are often patchy, containing a mosaic of different fire severities and unburnt areas within their perimeter, which may have implications for hydrologic connectivity (Cawson et al., 2012). Hydrologic connectivity is a measure of how effectively runoff and erosion producing areas connect to catchment outlets (Ambroise, 2004). In the broader hydrologic literature, the concept of hydrologic connectivity is often used to explain discrepancies in runoff volumes and sediment loads across different spatial scales (see reviews by Bracken and Croke, 2007; Ferreira et al., 2008; Michaelides and Chappell, 2009; Pringle, 2003). In the post-fire literature several authors acknowledge the potential significance of burn patchiness to hydrologic connectivity in burnt environments (e.g. Benavides-Solorio and MacDonald, 2005; Cawson et al., 2012; Ferreira et al., 2008; Kutiel et al., 1995; Richter et al., 1982; Smith et al., 2010) and some studies have sought to quantify those impacts (Moody et al., 2008; Robichaud and Monroe, 1997). Yet, overall the number of studies relating burn patchiness to post-fire hydrologic connectivity is limited, particularly in terms of empirical studies (as discussed by Cawson et al., 2012).

The aims of this study were to better understand the effects of (1) fire severity and (2) burn patchiness on post-fire runoff, erosion and hydrologic connectivity. Empirical data from a prescribed burnt dry eucalypt forest in Victoria (Australia) were collected to test the hypotheses that:

(1) Prescribed burning increases runoff and erosion rates.
(2) Increases in runoff and erosion rates following prescribed burning are related to the fire severity.
(3) Connectivity of surface runoff and erosion following prescribed burning depends on the size and arrangement of unburnt patches within the burn area.

Custom-designed hillslope runoff samplers were used to measure runoff and erosion under natural rainfall conditions. These runoff samplers were akin to unbounded runoff plots, except the plot openings were unusually narrow (0.1 m), making them operationally feasible for a single person to install and service. They also enabled many samplers to be installed on the same hillslope (16–20 per treatment), which provided a measure of variability.

## 2. Methods

### 2.1. Study site description

The study site was located in the eastern uplands of Victoria, Australia (Fig. 1). It was prescribed burnt in late April 2009 by the Department of Sustainability and Environment as part of a broader burn program. The burn resulted in unburnt, low and high fire severity patches, as described in Table 1.

Most of Victoria is in a temperate climate zone with no distinct dry season and mild to warm summers (depending on elevation) according to the Köppen classification (Bureau of Meteorology, 2005). The study commenced at the end of a long El Niño phase with annual rainfall in Victoria below average for 13 years from 1997 to 2009 (Bureau of Meteorology, 2010). However, for the duration of the study monthly rainfall totals were close to average or above average.

The vegetation was broadly classified as ‘dry eucalypt forest’ (Department of Sustainability and Environment, 2011). Dry eucalypt forests occur in well-drained soils where the mean annual rainfall is 600–1200 mm and the elevation is <750 m on northerly aspects. They can be distinguished from other forest types on the basis of vegetation structure (30–70% projected foliage cover and trees 10–30 m tall (Specht, 1970)), species composition and regenerative mechanisms following fire. Tree species at the site were *Eucalyptus dives*, *E. radiata*, *E. sieberi and E. cypellocarpa*. Those tree species typically regenerate from dormant buds on the trunk and branches following fire while the understorey species either regenerate from dormant soil-stored seed or seed released from woody capsules (Gill, 1994).

Bedrock at the site was sedimentary (folded siltstones, mudstones, shales and sandstones). The soil texture was classified as silty clay loam as determined using the pipette method for the finer fraction and sieving for the coarser fraction (Bowman and Hutka, 2002). The gravel content (>2 mm diameter) ranged from 15% to 46% throughout the site. The soil organic matter content ranged from 9% to 14% as determined using a loss on ignition method (samples heated in a muffle furnace at 550 °C for 3 h).

### 2.2. Field measurements

Unbounded runoff samplers were used to measure surface runoff and erosion from August 2009 (four months post-burn) to December 2010 (20 months post-burn). Fig. 2 illustrates the design of the samplers which consisted of box-guttering (0.1 m wide) and PVC pipe connected to a bucket. The capacity of the buckets was 17 L, except in three instances where the capacity was upgraded to 100 L after several 17 L buckets overflowed early in the sampling period. The samplers were installed in transects on planar hillslopes beneath six treatments (Fig. 3). To measure the effects of prescribed burning and fire severity on runoff and erosion rates (hypotheses 1 and 2) they were installed downslope of hillslopes with unburnt, low and high fire severities. To measure the effects of unburnt patches on hydrologic connectivity (hypothesis 3), additional samplers were installed on hillslopes with 1, 5 and 10 m wide unburnt patches downslope of low fire severity. There were 20 samplers on each transect, except downslope of the 1 m unburnt patch where there were only 16 samplers. Although the transects themselves were not randomly located, the samplers were randomly spaced along the transects. Distances between the samplers ranged from 0.1 to 2 m. The transects were located