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How soil temperatures during prescribed burning affect soil water repellency, infiltration and erosion

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A B S T R A C T

Fire can create, strengthen or destroy soil water repellency, with potential implications for soil infiltration, surface runoff and erosion. Laboratory studies suggest fire-induced changes to water repellency relate to soil temperatures during the burn. However, relations between temperature and repellency are rarely tested in the field where spatial variations in fuel type, soil type and soil moisture may lead to more complex responses to fire. Furthermore, few studies link point-scale water repellency measurements to hydro-geomorphic effects at larger spatial scales. Therefore, the purposes of this study were to (1) measure soil temperatures during prescribed burns, (2) investigate the in-situ effects of soil heating on soil water repellency and (3) investigate the subsequent effects of soil water repellency on infiltration, runoff and erosion. Heat-sensitive liquids and thermocouples measured soil temperatures at points within three prescribed burns. Soil water repellency and infiltration were measured at the same burnt points and at adjacent unburnt points 2–6 weeks post-burn. Rainfall simulations quantified plot-scale infiltration, surface runoff and erosion at one site. Peak temperatures at the surface were highly variable (averaging 238, 129 and 327 °C at each burn) while sub-surface temperatures were lower (averaging 75, less than 79 and 108 °C at each burn). Heating durations were short with surface temperatures greater than 400 °C lasting on average for 2 s and temperatures greater than 200 °C lasting on average for 6 s. Despite pre-existing water repellency in unburnt areas, water repellency was strengthened in burnt areas at two sites. High temperatures were associated with more repellency, even when the temperatures exceeded laboratory-defined thresholds for the destruction of water repellency. Short heating durations may explain why the laboratory-defined temperature thresholds were not applicable in the field. Point-scale steady-state infiltration rates were significantly lower for burnt compared with unburnt areas, reflecting the greater water repellency. However, other factors (e.g. macropore flow, soil sealing and reduced vegetation cover) are also likely to have caused unexpectedly high or low infiltration rates for some points and higher infiltration rates at the plot-scale than expected. The relative importance of water repellency to infiltration, surface runoff and erosion appeared to vary depending on the spatial scale of measurement. These issues of scale together with the apparent spatial heterogeneity of prescribed burnt landscapes warrant the use of connectivity modelling as a way to link point and plot scale measures to impacts at larger spatial scales.

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1. Introduction

Soil water repellency is considered important to post-fire hydrology, causing reduced infiltration and enhanced surface runoff and erosion, particularly after fire when the vegetation has been removed (see reviews by Certini, 2005; DeBano, 1981, 2000; Doerr et al., 2000; Letey, 2001; Shakesby et al., 2000). It has been recorded in many burnt and unburnt environments worldwide (Doerr et al., 2000) including in a range of eucalypt and coniferous forest soils (Doerr et al., 2009; Jordan et al., 2011; Keizer et al., 2008; Shakesby et al., 2007), and in the chaparral environment of southern California where is contributes to major flooding and erosion following fire (DeBano, 2000; DeBano et al., 1979). Soil water repellency is caused by organic material on the soil surface or in the soil profile (DeBano, 1981; Doerr et al., 2000); some plants containing resin, wax or aromatic oil are more commonly associated with it (e.g. eucalypts and pines) (DeBano, 1981; Doerr et al., 2000).

Fire can create, strengthen or destroy soil water repellency (DeBano, 2000; Doerr et al., 2000). Vaporised organic molecules on the soil surface, created by the combustion of organic matter, move into the soil profile along steep temperature gradients and condense as temperatures become cooler, forming a water repellent coating on the soil particles (DeBano, 1981). Numerous laboratory studies report temperature

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thresholds for the intensification and destruction of water repellency (e.g. DeBano, 2000; DeBano and Krammes, 1966; Doerr et al., 2004; Varela et al., 2005; Zavala et al., 2010). In summarising several laboratory studies, DeBano (2000) reported little change to water repellency for temperatures <175 °C, intensification of water repellency for temperatures from 175 to 200 °C and destruction of water repellency for temperatures from 280 to 400 °C. In eucalypt forest soil (sandy) from south-eastern Australia, Doerr et al. (2004) found that soils approached their maximum repellency when heated for five minutes from 250 to 280 °C while water repellency was eliminated for five minutes of heating from 310 to 340 °C. These laboratory studies show that in addition to temperature, other factors such as heating duration and oxygen supply are important. For example, Doerr et al. (2004) reported that water repellency was eliminated at lower temperatures when the heating duration was ten minutes (290 to 330 °C) compared with five minutes (310 to 340 °C). Bryant et al. (2005) showed that oxygen limitation can shift the destruction threshold for water repellency upwards by more than 200 °C.

While relationships between soil heating and soil water repellency are strong in the laboratory, few studies test those relationships under natural conditions in the field (exceptions include Stoof et al., 2011; Vadilonga et al., 2008). Vadilonga et al. (2008) reported a slight increase in water repellency for soil surface temperatures greater than 400 °C and a slight decrease for soil surface temperatures; less than 200 °C following a prescribed burn in Spain. Stoof et al. (2011) reported more persistent soil water repellency after an experimental burn in Portugal, despite low soil surface temperatures during the burn (60 °C). In both instances, the temperatures associated with changes to water repellency do not appear to be the same as those defined in laboratory studies. Factors such as soil moisture, oxygen supply, pre-existing water repellency, soil texture and type of organic matter are likely to make the relationship more complex in the field (Bodi et al., 2013; Bryant et al., 2005; Jordan et al., 2011; Keizer et al., 2008). If relationships between soil heating and water repellency in the field are similar to those defined in the laboratory, then measurements of water repellency could provide a useful post-hoc estimate of wildfire soil temperatures (Doerr et al., 2004).

Low infiltration rates and enhanced overland flow are often attributed to strong soil water repellency (Leighton-Boyce et al., 2007; Robichaud, 2000), though it is difficult to distinguish the importance of water repellency from other factors such as soil sealing and loss of vegetative cover (Doerr et al., 2003; Doerr and Moody, 2004; Larsen et al., 2009). If water repellency is moderately strong, then during a rainfall event the initially low infiltration rate may gradually increase as water repellency is broken down (DeBano, 1981; Robichaud, 2000). In relation to erosion, water repellency can enhance rill formation and raindrop splash erosion (DeBano, 2000; Shakesby et al., 1993). At hillslope and catchment scales the contribution of water repellency to enhanced runoff and erosion is unclear owing to its spatial variability and the presence of cracks, root holes, stones and other vertical macropores that can counteract the effects of water repellency (as discussed by DeBano, 2000; Doerr et al., 2003; Doerr and Moody, 2004; Ferreira et al., 2005; Urbanek and Shakesby, 2009).The spatial variability of water repellency may be particularly pronounced following low intensity fires or prescribed burns with numerous unburnt patches. These unburnt patches play an important role in reducing runoff and erosion at the hillslope scale (Cawson et al., 2012, 2013). Combining measures of water repellency with measures of infiltration, runoff and erosion following burning is important for better understanding the hydrological and geomorphic implications of water repellency.

This study aimed to quantify field-based relations between temperature and water repellency and the hydro-geomorphic implications of water repellency following prescribed burning. Specifically, the purposes were to (1) measure soil temperatures during prescribed burns, (2) investigate the in-situ effects of soil heating on soil water repellency and (3) investigate the subsequent effects of soil water repellency on infiltration, runoff and erosion. The study was located in the dry *Eucalyptus* forests of Victoria, Australia (described by Nyman et al., 2011) within three prescribed burns that were conducted by the Victorian Government as part of their routine burning program to reduce wildfire risk. As governments set ambitious targets to increase the area that is prescribed burnt (e.g. Parliament of Victoria, 2010), it is important to understand and manage its potential impact on a range of ecosystem services including water supply (Cawson et al., 2012).

Dry *Eucalyptus* forests are especially prone to surface runoff and erosion following fire and high severity wildfire can greatly increase the susceptibility of these forests to extreme erosion events including debris flows (Noske et al., 2016; Nyman et al., 2011; Sheridan et al., 2015). Debris flows pose substantial risks to water quality within the forested water supply catchments surrounding Melbourne (Smith et al., 2011) and thus further hydrological and geomorphological research is warranted in these drier forest types. Dry *Eucalyptus* forests are frequently targeted for prescribed burning (Cawson, 2012) and debris flows have been noted to occur following prescribed burning (Cawson et al., 2012). Yet little research exists about the likelihood of extreme erosion following low intensity burning. Existing hydrological research about low intensity fire in dry *Eucalyptus* forests suggests that spatial patterns of burning and patchy impacts are important determinants of the hillslope response (Cawson et al., 2013; Morris et al., 2014; Smith et al., 2010).

2. Methods

2.1. Study sites

The three study sites, Upper Yarra, Big Ben and Mt. Cole, were located in prescribed burns in the uplands of Victoria, Australia (Fig. 1, Table 1). These prescribed burns were chosen (1) for logistical reasons because they were high priority burns (most likely sites to be burnt) with good road access and (2) for study design purposes because they the contained the same broad vegetation type but contrasting soil types enabling the post-fire response to be assessed across variants of the same vegetation. The vegetation at the sites was broadly classified as dry *Eucalyptus* forest based on the Victorian Government's Ecological Vegetation Classification System. Dry *Eucalyptus* forests occur in well-drained soils where the mean annual rainfall is between 600 and 1200 mm and the elevation is less than 750 m. They can be distinguished from other eucalypt 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. The sites had contrasting understoreys; shrubby with a patchy cover of surface litter and some tufted grasses at Upper Yarra; grassy with sparse surface litter at Big Ben; shrubby with tufted grasses and relatively deep surface litter containing ribbons of bark at Mt. Cole (Fig. 2). The underlying geology differed between the sites with a sedimentary substrate (folded siltstones, mudstones, shales and sandstones) at Upper Yarra, a metamorphic substrate (schist and gneiss) at Big Ben and an igneous (granitic) substrate at Mt. Cole. Similarly, the soil textures differed between the sites with silty clay loam at Upper Yarra and Big Ben and sandy loam at Mt. Cole. The Upper Yarra site was last burnt by wildfire in 1939, the Big Ben and Mt. Cole sites were both last burnt by prescribed burns in 2002 and 1994, respectively (Department of Sustainability and Environment, 2011).

The burns were carried out by the Victorian Government as part of their prescribed burning program. Upper Yarra and Big Ben were burnt in April 2009 and Mt. Cole in March 2010. The weather conditions were mild, with maximum temperatures of approximately 20 °C, minimum relative humidities of 50–60%, light winds and fuel moisture contents of 10–15% for surface litter and 11–16% for profile litter. All the instrumented hillslopes were lit with handheld drip torches.

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