Effects of prescribed burning on surface runoff and erosion

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Abstract

Prescribed burning – the deliberate use of fire to achieve management objectives – is used extensively in fire-prone vegetation for reducing fuel hazards and enhancing ecological values. As governments set ambitious targets for more prescribed burning, it is important to understand and manage the potential negative impacts, such as increased erosion. While globally there are many studies that consider the effects of prescribed burning on surface runoff and erosion, there are critical knowledge gaps for particular forest types (e.g. dry eucalypt forests) and in relation to understanding the factors controlling particular post-fire hydrologic and erosion responses, the likelihood of large impacts, the effects of spatial scale on the magnitude of an impact and the long-term risks of repeated burning. Therefore, the aim of thesis was to quantify the effects of prescribed burning on soil hydrologic properties, surface runoff and erosion in dry eucalypt forests in Victoria, Australia.

This aim was addressed by examining the effects of two potentially important aspects of fire regimes – fire severity and burn patchiness – on soil hydrologic properties, surface runoff and erosion. Measurements were conducted in unburnt, low fire severity (scorched understorey and intact canopy) and high fire severity (burnt understorey and scorched canopy) areas at three dry eucalypt forest sites. Soil water repellency (using the critical surface tension test) and infiltration capacity (using ponded and tension infiltrometers) were measured at the point-scale for all sites immediately post-burn and then at six-month intervals. Rainfall simulations were used to measure runoff and erosion at the plot-scale (3 m^2) six-weeks and 11-months post-burn at one site. Additionally, at one site runoff samplers (116 unbounded plots, 10 cm wide and approximately 100 m from the catchment divide) were used to measure runoff and erosion downslope of six burn categories: (1) high severity, (2) low severity, (3) unburnt, and low severity above (4) 1 m, (5) 5 m, and (6) 10 m wide unburnt patches.

Prescribed burning resulted in higher runoff and erosion rates. Cumulative hillslope runoff volumes (over16-months) were approximately two orders of magnitude higher on burnt hillslopes and cumulative sediment loads were approximately three orders of magnitude higher. Water repellency increased following burning at two sites, but loss of vegetation cover appeared to be the primary driver for increased runoff and erosion in burnt areas, as fire-induced water repellency did not affect point-scale infiltration capacities. Fire severity differences had relatively little effect on runoff and erosion, presumably because surface vegetation cover was similar in the high and low fire severities.

Unburnt patches were highly effective at reducing the connectivity of runoff and erosion from upslope burnt areas, with reductions in overall sediment loads of 96.6% and 99.8% for the 5 m and 10 m wide patches, respectively. The effectiveness of the unburnt patches at reducing runoff and erosion connectivity varied with patch width and rainfall intensity. For example, the 1 m wide unburnt patch reduced the overall sediment load by 92% for rainfall events with average recurrence intervals of < 10 years but was ineffective during a 10-year storm. Overall, the results suggested that despite higher plot-scale runoff and erosion rates post-burn, prescribed burns are unlikely to substantially affect runoff and erosion at the catchment-scale for most rainfall events given their inherent patchiness. Only during particularly intense storms, when unburnt patches become less effective at intersecting runoff and erosion, might severe erosion occur.

From a management perceptive, the results suggest that to minimse runoff and erosion connectivity and potential water quality impacts following prescribed burning, there should be a fine-grained mosaic of burnt and unburnt patches throughout a burn (e.g. > 50% unburnt and patches 5-10 m wide) and unburnt streamside buffers. Such burn patterns may be achieved by the ignition pattern, and burning under mild conditions when there are moisture differentials throughout the burn area. While fire severity was found to be a less significant factor in relation to post-burn runoff and erosion rates, it is likely that lower fire severities are associated with more patchy burns and therefore it would be reasonable to aim for low severity burn outcomes.

Declaration

This is to certify that:

1. The thesis comprises only my original work towards the PhD except where indicated in the acknowledgements section.
2. Due acknowledgement has been made in the text to all other material used.
3. The thesis is fewer that 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

Some of the research presented in this thesis was peer-reviewed and published before the final submission of this thesis:

- Cawson, J. G., Sheridan, G. J., Smith, H. G. and Lane, P. N. J. (2011) The effect of prescribed fire severity and burn patchiness on runoff and erosion. In Proceedings of Bushfire CRC and AFAC 2011 Conference Science Day (Sydney).
- Cawson, J. G., Sheridan, G. J., Smith, H. G. and Lane, P. N. J. (2012) Surface runoff and erosion after prescribed burning in forests and shrublands, and the effect of different fire regimes: a review. International Journal of Wildland Fire, 21, 857-872.

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1. Introduction

1.1 Problem statement and aim

Undisturbed forests are typified by low rates of surface runoff and erosion because high levels of organic matter, high porosity and deep litter on the soil surface facilitate infiltration and inhibit erosion (Lane *et al.* 2004; Neary and Ffolliott 2008; Neary *et al.* 2009). Fire increases the susceptibility of forests 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; Shakesby *et al.* 2007; Wondzell and King 2003). As a result, hillslope erosion rates and instream concentrations of suspended sediments, nutrients and other constituents can be much higher in forest streams after fire (Neary *et al.* 2008a; Smith *et al.* 2011c).

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.* 2011c), recreation and aesthetics (Smith *et al.* 2011a; Smith *et al.* 2011c). 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.* 2011c); following an intense 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) and elevated erosion on hillslopes may have other ecological impacts such as the loss of soil-stored seed and nutrients.

Prescribed burning is the deliberate use of fire to achieve specified objectives (Graham *et al.* 2010; Tolhurst and Cheney 1999). Its prevalence fluctuates as government policies and community perceptions about fire change (Graham *et al.* 2010; Oliveras and Bell 2008). Currently in southern Australia and in the western United States the preference is for more prescribed burning (Parliament of Victoria 2010; USDA Forest Service 2000) to reduce fuel hazards and promote ecological values. For example, in Victoria, Australia, the annual target for prescribed burning has increased from 1.6% of public land (~130,000 ha y^{-1}) in the mid-2000s to 5% of public land (390,000 ha y^{-1}) by 2014 (Parliament of Victoria 2008, 2010). As governments set these ambitious prescribed burning targets, it is important to understand and manage potential negative impacts, such as increased erosion.

While globally there are many studies that consider the effects of prescribed burning on surface runoff and erosion (Table 1 in Chapter 2), there are critical knowledge deficits for particular forest types (e.g. dry eucalypt forests). Dry eucalypt forests (Department of Sustainability and Environment 2011c) are the predominant forest type targeted for prescribed burning in Victoria, Australia (60% of the area prescribed burnt from 1988 to 2008 was in dry eucalypt forest; Figure 18 in Chapter 3) yet, for this forest type there is little research about the effects of prescribed burning on surface runoff and erosion. In fact, there are very few papers on the topic across all forest types in Australia (Ronan 1986; Smith *et al.* 2010; Townsend and Douglas 2000). The vast majority of forest-based research about the effects of prescribed burning on runoff and erosion is from North American conifer forests (Shakesby and Doerr 2006). Differences between those North American forests and Australian dry eucalypt forests, in relation to factors such as vegetation, litter, soil properties, faunal activity and micro-scale surface features (Shakesby *et al.* 2007), suggest that the research from North America may not directly apply to dry eucalypt forests.

Additionally, there are a number of specific knowledge gaps for all forest types in relation to the effects of prescribed burning on surface runoff and erosion. These knowledge gaps (discussed in Chapter 2) relate to understanding the factors controlling particular post-fire hydrologic and erosion responses, quantifying the likelihood of large impacts, understanding the effects of spatial scale on the magnitude of an impact and quantifying the long-term risks associated with repeated burning. One of the recommendations from Chapter 2 is that further process-based studies are conducted to understand the factors controlling surface runoff and erosion; this thesis seeks to address that recommendation.

The broad aim of this thesis is to quantify the effects of prescribed burning on soil hydrologic properties, surface runoff and erosion in dry eucalypt forests. This is achieved by setting a number of specific hypotheses based on a conceptual model of the system, and testing those hypotheses with a series of field-based measurements.

1.2 Scope

The scope is limited to a single forest type – dry eucalypt forest. As mentioned previously, dry eucalypt forests are often burnt by prescribed fire in Victoria (Figure 1 in Chapter 3) and are rarely studied in relation to post-fire runoff and erosion research (one exception is Nyman *et al.* 2011). The hypotheses tested relate specifically to the effects of fire severity and burn patchiness on soil hydrologic properties, surface runoff and erosion. The rationale for focusing on those characteristics of the fire regime is discussed in the research design chapter (Chapter 3). The measurements of soil hydrologic properties, runoff and erosion occur at a range of spatial scales from point to hillslope, and the results are extrapolated to the catchment-scale in the final chapter.

1.3 Thesis structure

To achieve the above aim, Chapter 2 reviews existing literature about the effects of prescribed burning on surface runoff and erosion, and the fire regime factors controlling those processes. The purpose of the literature review is to provide the background for developing a conceptual model about the hydrologic and erosional response of dry eucalypt forest to prescribed burning. This conceptual model is presented in Chapter 3 together with a shortlist of hypotheses that stem from the conceptual model; the validity of those hypotheses is tested throughout the thesis. Chapter 3 also introduces the methods and the study sites and acts as a road map for the rest of the thesis.

The results are presented in Chapters 4 to 7, together with descriptions of the measurement techniques and discussions relating to the hypotheses addressed by those measurement techniques. The measurements in each results chapter occur at different spatial scales. Chapters 4 and 5 both test hypotheses about the effects of fire severity at the point-scale (Chapter 4 is concerned with soil heating and soil water repellency while Chapter 5 is concerned with soil infiltration capacity), Chapter 6 tests hypotheses about the effects of fire severity on infiltration, runoff and erosion at the plot-scale, and Chapter 7 tests hypotheses about the effects of fire severity and burn patchiness on runoff and erosion at the hillslope-scale.

Chapter 8 draws together the conclusions from each of the results chapter to readdress the overall aim of the thesis and reflect on the implications of the research both conceptually in relation the conceptual model and from a management perspective.

2. Literature review

This chapter examines the state-of-knowledge about the effects of prescribed burning on surface runoff and erosion at point to catchment scales. Two directions for future research are recommended: (1) process-based studies to understand the factors controlling surface runoff and erosion, particularly in relation to aspects of the fire regime, and (2) landscape-scale surveys to quantify large erosion events.

2.1 Introduction

Prescribed burning – the deliberate use of fire to achieve specified objectives – is a popular land management tool in fire-prone landscapes (Bird *et al.* 2008; Ferreira *et al.* 2005; Neary *et al.* 1999; Tolhurst and Cheney 1999; 2000). 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 such as biodiversity (Bond and Archibald 2003; Gill 2008), water supply (Smith *et al.* 2011c), and carbon sequestration (Wiedinmyer and Hurteau 2010). Some ecosystem services may be enhanced by prescribed burning, whereas others may be adversely affected. This chapter considers the effects of prescribed burning on surface runoff and erosion by reviewing the existing literature and presenting an example of highly elevated erosion following prescribed burning. Runoff and erosion can reduce water quality in streams and reservoirs, which is a problem for aquatic ecology (Minshall 2003), human consumption (Smith *et al.* 2011c) and other uses (e.g. agriculture, recreation); and high magnitude erosion (e.g. debris flows) poses a threat to property and human safety and may also have environmental impacts (Cannon *et al.* 2010).

Fire can increase surface runoff and erosion rates by removing vegetation, changing the soil's hydrologic properties, and providing a readily erodible layer of sediment and ash (see reviews by Certini 2005; Neary *et al.* 1999; Shakesby 2011; Shakesby and Doerr 2006; Shakesby *et al.* 2007; Wondzell and King 2003). The fire regime – characteristics of fire in a particular area and over time

(Krebs *et al.* 2010) – is likely to influence the extent of those changes, as discussed by Neary *et al.* (1999) in relation to fire severity and Benavides-Solorio and MacDonald (2005) in relation to burn patchiness. Other factors are also important, such as post-fire rainfall (Smith *et al.* 2011c) and site characteristics (Martin and Moody 2001). The largest surface runoff and erosion events occur during intense storms, whereas in the absence of significant rain, fire has been found to have little effect on runoff and erosion (Smith *et al.* 2011c).

This chapter determines the current state of knowledge about the effects of prescribed burning on runoff and erosion in forests and shrublands, and the factors controlling those effects. First, existing literature relating specifically to prescribed burning is examined, and an example from south-eastern Australia is presented to illustrate that high magnitude erosion can be caused by prescribed burning. Following that, research relating characteristics of fire regimes to post-fire runoff and erosion is reviewed – while many factors are important to post-fire runoff and erosion, we focus on the fire regime because it can be manipulated by fire managers to improve burning practices. Next, the relationship between the fire regime and rainfall is considered to demonstrate that post-fire erosion depends on an interaction between several factors. Finally, in the conclusions, some recommendations are made for future research.

2.2 Existing research on surface runoff, erosion and water quality after prescribed burning

Of the many studies that consider the effects of prescribed burning on surface runoff and erosion (Table 1 summaries some of those studies), a high proportion report that the impacts are minimal. In particular, the catchment-scale studies – involving instream sampling of properties such as suspended sediment concentrations (Scott 1993; Smith *et al.* 2010; Townsend and Douglas 2000), concentrations of various anions and cations (Elliot and Vose 2005; Richter *et al.* 1982; Stephens *et al.* 2004), and aquatic ecology (Arkle and Pilliod 2010; Bêche *et al.* 2005) – often report minimal impacts. Plot- and hillslope-scale studies detect more substantial impacts more frequently (Benavides-Solorio and

MacDonald 2005; Morales *et al.* 2000; Robichaud 2000; Robichaud *et al.* 2007), though not always (Elliot and Vose 2005; Ronan 1986).

Although the catchment-scale studies provide valuable insights into the effects of prescribed burning under particular conditions, they only represent a small sample of prescribed burns and post-fire rainfall conditions. For example, typically more than 100,000 hectares are prescribed burnt in Victoria, Australia, every year, yet post-burn water quality has only been measured in two small (133 ha and 87 ha) catchments during below-average rainfall conditions (Smith *et al.* 2010). Large erosion impacts following prescribed burns are likely to be infrequent events requiring intense storms to occur in a burnt area (e.g. Section 2.3). To capture these events in a catchment-scale study, a large number of studies would be required – e.g. if the threshold storm required to trigger a debris flow in a prescribed burn had an average recurrence interval of 20 years then a single, recently burnt catchment would need to be studied for over 13 years to have even a 50% chance of detecting a debris flow.

Several factors influence erosion susceptibility following fire and the likelihood of an erosion event occurring – the studies described in Table 1 identify some of these factors. Low fire severity (e.g. Arkle and Pilliod 2010; Fernández *et al.* 2008; Richter *et al.* 1982; Savadogo *et al.* 2007) and burn patchiness (e.g. Richter *et al.* 1982; Smith *et al.* 2010) are often cited as potential explanations for observed small impacts following prescribed burning. Some studies identify the spatial extent of the burn as an important factor – i.e. they suggest that the instream effects of burning were diluted because the prescribed burn only affected part of the catchment (Bêche *et al.* 2005; Richter *et al.* 1982; Townsend and Douglas 2000). Below average rainfall is another frequently cited factor (e.g. Elliot and Vose 2005; Galang *et al.* 2010; Smith *et al.* 2010). Although below-average rainfall can affect any hydrological study that depends on natural rainfall, its effects may be further exacerbated in prescribed burning studies where the threshold amounts of rainfall required to trigger runoff and erosion are high (Neary *et al.* 2008b).

In addition to potentially causing infrequent but high magnitude runoff and erosion events, there may also be water quality impacts caused by the persistent supply of water quality constituents at concentrations slightly above those in undisturbed forests. The effects of an individual prescribed burn may be small and only last for a short period – e.g. < 1 year (Bêche *et al.* 2005) or < 3 months (Stephens *et al.* 2004) – but the cumulative effect of multiple, smaller prescribed burns within the same catchment may be a larger, longer-term issue. Prescribed burning studies rarely occur at spatial and temporal scales that are suitable for detecting these possible cumulative effects.

Table 1: A sample of studies about prescribed burning effects on runoff, erosion and water quality. Qualitative ratings for the 'significance of change' are based on inferred implications described in the paper. Reasons for small changes are: (a) low fire severity, (b) burn patchiness, (c) unburnt riparian zone, (d) low rainfall following the burn, (e) dilution of effects because the size of the burn was small relative to the size of the catchment, (f) low slopes, n/a means not applicable.

	Vegetation	Author	Location	Hydrological variables investigated	Type of measurements	Change detected	Variables that changed	Significance of change	Reason for small change
North America	Mixed conifer	Arkle & Pilliod (2010)	Idaho	Aquatic organisms, habitat	Instream	No	n/a	n/a	a, c
		Bêche et al. (2005)	California, USA	Suspended sediment, water chemistry, aquatic organisms	Instream	Yes	Water chemistry, aquatic organisms	Minor – short duration (< 1 year)	a, d, e, f
		Galang et al. (2010)	South Carolina, USA	Flow in small eroded gullies in former cotton fields	Instrumented gullies	No	n/a	n/a	d
		Richter et al. (1982)	South Carolina, USA	Various cations & anions	Instream	No	n/a	n/a	a, b, c, e
		Stephens et al. (2004)	California, USA	Soil: total C & N, P, NH_4^+ & NO_3^- & pH; Instream: NO_3^-, soluble reactive P, Ca^+, Mg^{2+}, K^+, SO_4^{2-}	Hillslope soil samples, instream	Yes	All soil variables except nitrate; instream Ca^+, Mg^{2+}, sulphate	Minor – small change, < 3 month duration	a,f
		Morales et al. (2000)	Mexico	Runoff	Hillslope plots	Yes	Runoff	Moderate – runoff increased by up to 42%	Largest increases were for the most severely burnt plots & for repeatedly burnt plots
		Benavides-Solorio & MacDonald (2005)	Colorado, USA	Erosion	Hillslope sediment fences	Yes	Sediment yield	Moderate	a, b
		Benavides-Solorio & MacDonald (2001)	Colorado, USA	Runoff, erosion	Rainfall simulation plots (1 m^2)	Yes	Sediment yield	Moderate – for high severity areas	a – fire severity strongly related to sediment yield
		Robichaud et al. (2007)	Idaho, USA	Runoff, erosion on ash-cap soils	Rainfall simulation plots (1 m^2)	Yes	Runoff ratio, sediment yield	Minor to moderate depending on fire severity	a – highest runoff ratios and sediment yields in higher severity plots.
		Robichaud (2000)	Montana & Idaho, USA	Infiltration, runoff	Rainfall simulation plots (1 m^2)	Yes	Infiltration, runoff	Not discussed	n/a
	Mixed pine-oak forest	Elliot & Vose (2005)	Tennessee & Georgia, USA	Various anions & cations, pH, suspended sediment	Hillslope soil samples & instream	No	n/a	n/a	a, b, d
	Sagebrush-steppe	Pierson et al. (2009)	Idaho, USA	Infiltration, runoff, erosion	Rainfall simulation plots (0.5 m^2 & 32.5 m^2) & concentrated flow simulations	Yes	Infiltration, runoff, erosion	Not discussed	n/a
Europe	Shrubland with pine	Vadilonga et al.(2008)	Catalonia, Spain	Infiltration, soil water storage, water repellency	Points on hillslope, rainfall simulation	Yes	Soil water storage, water repellency	Minor – no changes to runoff expected	a – changes were larger for more severely burnt plots
	Shrubland	Stoof et al.(2012)	North-central Portugal	Streamflow, throughfall, soil moisture	Instream, points on hillslope	Yes	Streamflow, throughfall	Moderate	a
	Gorse shrubland	Vega et al.(2005)	Galicia, Spain	Throughfall, runoff, erosion	Runoff plots, throughfall troughs	Yes	Throughfall, runoff, erosion	Minor	a – magnitude and duration of change was dependent on fire severity; d

	Vegetation	Author	Location	Hydrological variables investigated	Type of measurements	Change detected	Variables that changed	Significance of change	Reason for small change
	Mixed Heathland	Fernández et al. (2008)	Galicia, Spain	Infiltration, runoff, erosion	Rainfall simulation plots (1 m^2)	Yes	Infiltration, runoff, erosion	Minor	a – erosion rate less due to retention of organic layer after burning
Australia	Eucalypt forest	Ronan(1986)	Victoria, Australia	Runoff, sediments, nutrients	Runoff plots	Yes	Runoff, sediment (mainly in high severity)	Minor	a
		Smith et al. (2010)	Victoria, Australia	Suspended sediments, phosphorus, nitrate	Instream	Yes	Suspended sediment, phosphorus	Minor	a, b, c, d
	Tropical savanna	Townsend & Douglas (2000)	Northern territory, Australia	Suspended sediment, N, P, Fe, Mn	Instream	Yes	Suspended sediment for late season burn only	Minor	d, f, e, soil fertility
Africa	Fynbos	Scott (1993)	Jonkershoek, South Africa	Streamflow, stormflow, suspended sediment	Instream, points on hillslope	Yes	Annual streamflow	Minor	Low fuel loads; moist fuels & soil during the burn; rapid regeneration
	Savanna woodland	Savadogo et al. (2007)	Burkina Faso, West Africa	Infiltration	Points on hillslope	Yes	Infiltration	Minor	a – vegetation was moist at time of burn

2.3 An example of high magnitude erosion following a prescribed burn

The following example demonstrates that severe erosion may occur following prescribed burning. It describes the conditions contributing to several debris flows following a prescribed burn, while the neighbouring unburnt catchment was unaffected. This example is significant because there are no other examples in the literature of such severe erosion following prescribed burning. The current prescribed burning literature is limited in its ability to quantify the frequency of such events and the factors controlling their occurrence.

The debris flows occurred after a low fire severity prescribed burn in north-eastern Victoria, Australia (Figure 1) (36^{o} 44' 48" S, 144^{o} 53' 58" E). They were characterized as debris flows on the basis of field evidence outlined by Nyman *et al.* (2011) – e.g. unstratified sediment deposits, matrix filling voids between large clasts within the deposit, severe scarring on the upstream side of tree trunks and severely eroded channels (Figure 2). The catchments were steep by Victorian standards (mean slope 18^{o}, 29% > 25^{o}, 14% > 30^{o}) and converging with a northerly aspect and sedimentary (marine) mudstone and siltstone geology. The vegetation was grassy dry eucalypt forest (Department of Sustainability and Environment 2011c) and long unburnt (> 20 years). The prescribed burn was conducted in April 2009, which is a popular time for prescribed burning in Victoria. Usually at this time of the year fuel moisture contents have increased from summer conditions (due to rainfall and higher dew points overnight) but remain low enough for burning to occur (i.e. fine fuel moisture contents of 10-16%) (Tolhurst and Cheney 1999). The burn resulted in burnt surface fuels, unburnt or scorched shrubs, and an intact tree canopy on the upper slopes of the catchment (Figure 2). Charred grass tufts remained, suggesting that the burn was not particularly hot and that fibrous roots were probably unaffected. On the lower slopes the vegetation was mostly unburnt. At the time of the debris flow (in January 2010) the surface vegetation was regenerating.

The storm responsible for the debris flow in the prescribed burn was particularly intense for this location (I_{30} of 51 mm h^{-1}) (Figure 3), exceeding the peak intensities associated with post-wildfire debris flows (I_{30} of 35 mm h^{-1}) in this region (Nyman *et al.* 2011). There was no evidence of erosion in an adjacent unburnt catchment. The amount of soil removed was not measured; however, it is likely to be less than the amounts measured in similar wildfire-burnt catchments owing to infiltration and sediment trapping within unburnt patches on the prescribed burnt hillslope. Nyman *et al.* (2011) measured sheet erosion depths of 4.6 - 18.4 mm and average channel entrainment of 0.6 - 1.4 m^3 m^{-1} in similar wildlife-burnt catchments in Victoria, Australia.

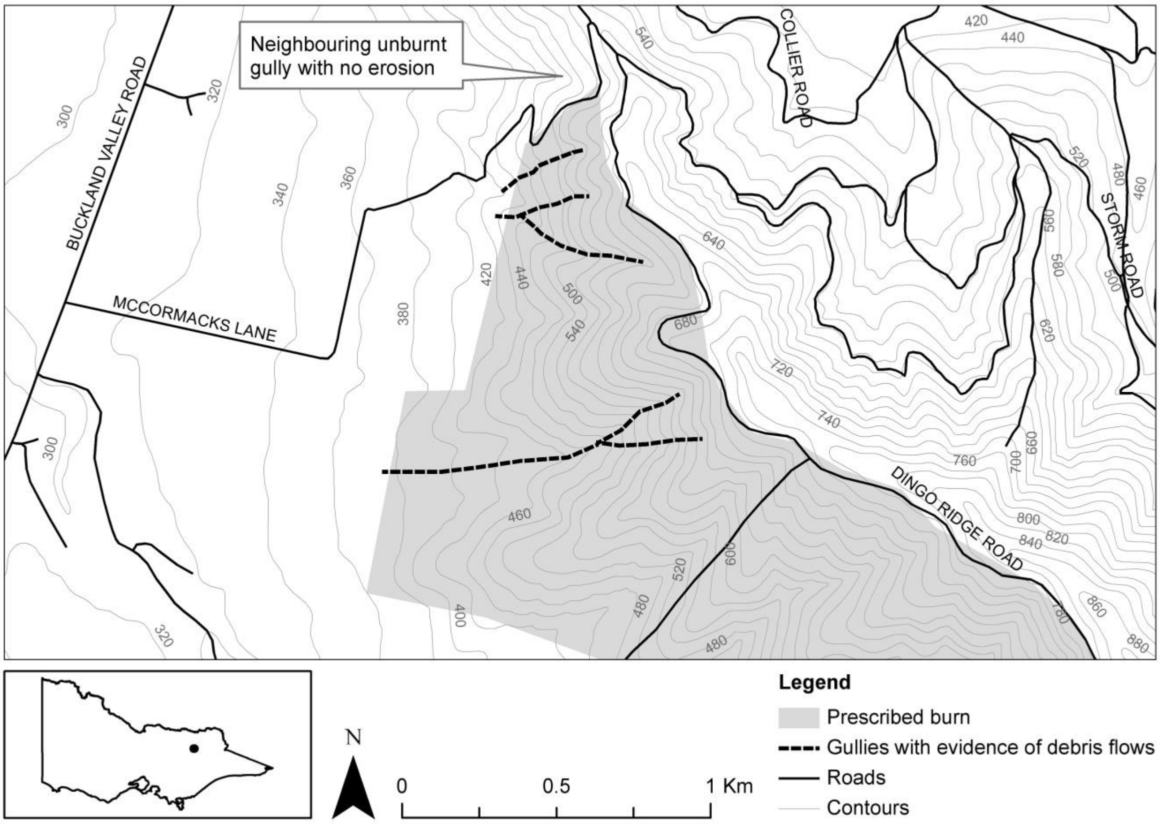


Figure 1: Location of debris flows in prescribed burnt catchments (map centre: 36° 44' 48'' S, 144° 53' 58'' E) in north-eastern Victoria, Australia. The lines denote the gullies affected by debris flows, not the debris flow length. Fire severity was not mapped for this prescribed burn, but it was generally low (patchy burn in understorey and intact canopy) with numerous unburnt patches.

Figure 2: Photographs to illustrate site conditions six-months after a debris flow in a prescribed burn in north-eastern Victoria, Australia: (a) appearance of vegetation in the catchment area – low fire severity (patchy burn in understorey, intact canopy) and substantial recovery; (b) channel erosion in the upper catchment; (c) severe scarring on the upstream side of a tree trunk; (d) sediments deposited in the lower catchment; (e) main depositional area.

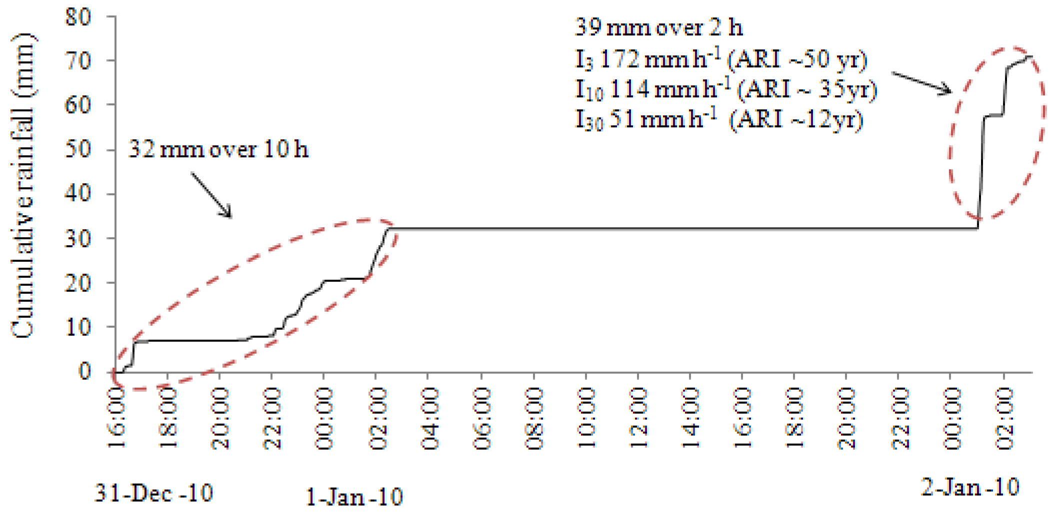


Figure 3: Rainfall contributing to the debris flows in the prescribed burn in north-eastern Victoria, Australia. The debris flow occurred on the 2nd January 2010. Data were collected from Bureau of Meteorology weather station at Bright (7.5 km north-east of the debris flow).

2.4 The effect of different characteristics of the fire regime on surface runoff and erosion

The fire regime is often cited as an important factor distinguishing the erosion and water quality response of prescribed burns to that of intense wildfires (Arkle and Pilliod 2010; Benavides-Solorio and MacDonald 2005; Richter *et al.* 1982). Fire regime is a broad concept that may be interpreted differently depending on the context (Gill and Allan 2008; Krebs *et al.* 2010). Generally (as stated in the introduction) it is a description of the characteristics of fire in a particular area and over time (Krebs *et al.* 2010). These characteristics are wide-ranging depending on the type of environmental, economic or social effect being considered (Gill and Allan 2008; Krebs *et al.* 2010). In relation to surface runoff, erosion and water quality, the characteristics of the fire regime likely to be most important are fire severity (see definition below), burn patchiness, burn season and fire frequency.

Fire regimes can be manipulated by land managers to achieve various objectives such as to reduce the impact of wildfires on human property, potable water supplies and timber, or to promote particular plant species or vegetation structures (e.g. Cheal 2010; USDA Forest Service 2000). Given that the fire regime can be manipulated using prescribed burning, it is worth studying from a management perspective as a better understanding of their relationship to runoff and erosion could be used to determine the most suitable fire regimes for minimising surface runoff and erosion.

2.4.1 **Fire severity**

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). Indicators of fire severity are typically associated with vegetation and/or soils. The vegetation related indicators include the amount of unburnt, scorched and burnt vegetation in each vegetation stratum, the scorch height and the smallest diameter of woody fuel remaining (e.g. Chafer 2008). The soil-related indicators (most commonly used in the USA) include surface colour changes, loss of soil structure, consumption of fine roots and the formation of soil water repellency (Parsons *et al.* 2010).

Prescribed burns are usually dominated by low fire severity areas, meaning that the surface fuels are burnt (partially or completely) but the canopy is intact. Fire severity 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 understanding 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 (Benavides-Solorio and MacDonald 2001; Benavides-Solorio and MacDonald 2005; Doerr *et al.* 2006; Dragovich and Morris 2002; Huffman *et al.* 2001; Robichaud 2000; Vadilonga *et al.* 2008; Woods *et al.* 2007).

The relationship between fire severity and post-fire runoff and erosion, is 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). Overall, less runoff and erosion are reported for low fire 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). However, there remains much to learn about the mechanisms that distinguish the fire severity classes in terms of their runoff and erosion characteristics.

2.4.1.1 Heating-induced soil changes

The most widely researched soil property affected by soil heating is soil water repellency. Several literature reviews discuss many aspects of water repellency including the results of laboratory studies that show how soil water repellency can be created, strengthened, relocated or destroyed as a result of heating (DeBano 2000; DeBano *et al.* 2008; Doerr *et al.* 2000; Letey 2001). The effect of heating on soil water repellency depends on the temperatures reached, the duration of heating and the extent of pre-existing water repellency. At the plot-scale, 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; DeBano *et al.* 2008; Terry and Shakesby 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 (as discussed by DeBano 2000; Doerr *et al.* 2003; Doerr and Moody 2004; Ferreira *et al.* 2005; Urbanek and Shakesby 2009) – see discussion in Section 2.4.2.

Other important soil properties affected by soil heating are soil organic matter, critical shear stress and aggregate stability. Consumption of organic matter is substantial at 200-250^{o}C and completed at 460^{o}C (summarised by Certini 2005). As organic matter is lost from the soil, its structure degrades and macroporous flow diminishes; this leads to increased runoff (DeBano *et al.* 1979; Neary *et al.* 1999). Critical shear stress affects the susceptibility of some soils to erosion. It is most variable (1.0 - 2.0 N m^{-2}) at < 175 ^{o}C, reaches a maximum (> 2.0 N m^{-2}) between 175 ^{o}C and 275 ^{o}C, and is constant (0.5 - 0.8 N m^{-2}) for temperatures > 275 ^{o}C (Moody *et al.* 2005). Heating both reduces and increases the strength of soil aggregates, depending on the temperatures reached; lower temperatures (e.g. 250 – 350 ^{o}C) enhance the strength of soil aggregates while higher temperatures (e.g. 450 ^{o}C) cause the volatilisation of aggregate binding organic material and therefore a loss of soil aggregate stability (Blake *et al.* 2009). Soil aggregation affects the soil's structure and erodibility (Blake *et al.* 2009), and settling velocities (Droppo 2001).

Although relationships between soil heating and changes to soil hydrologic properties are clearly demonstrated in laboratory trials, predicting those changes in the field – using fire severity as a surrogate for soil heating – yields inconsistent results. For example, Doerr *et al.* (2006) reported a decrease in water repellency at the surface for high fire severities while Woods *et al.* (2007) reported an increase (Table 2). These inconsistencies probably occur because there are often poor correlations between fire severity and soil heating as a result of several factors – e.g. natural variability between the study sites (in terms of soil moisture, soil type and vegetation type), different definitions for each fire severity class, and poor correlations between some fire severity metrics (e.g. percentage crown scorch) and soil heating. These poor correlations between fire severity and soil heating are evident in Table 3, where the temperatures recorded for low fire severity and high fire severity areas overlap – surface temperatures range from 37 ^{o}C (Vega *et al.* 2005) to 800 ^{o}C (Stoof 2011) and from < 60 ^{o}C (Stoof 2011) to 925 ^{o}C (Odion and Davis 2000) in low and high severity areas, respectively. Relationships between soil heating and changes to soil properties may also differ in the field from the relationships demonstrated in the laboratory. For example, Stoof *et al.* (2011) reported more persistent soil water repellency after an experimental burn, despite low soil temperatures during the burn (i.e. 60 ^{o}C). This water repellency may have been caused by a very thin layer of dry surface soil or by small quantities of water repellent ash mixed into the surface soil.

Another important point in relation to soil heating and its effects on soil hydrologic properties is that there is limited research linking changes to soil hydrologic properties to post-fire runoff and erosion at larger spatial scales (Ferreira *et al.* 2008; Shakesby *et al.* 2000). This issue is discussed by Ferreira *et al.* (2008) and Shakesby *et al.* (2000) in relation to soil water repellency – although water repellency may be intensified by fire at the point-scale, wettable patches and other sources of infiltration may prevent water repellency from affecting runoff to the same extent at larger spatial scales.

Table 2: A selection of papers reporting soil heating for different fire severities during prescribed burns.

Location	Above[B] or below ground	Low severity	High severity	Author
Tropical eucalypt savanna in Australia[A]	Above	182 °C (mode)	>182 °C (mode)	Williams *et al.* (2004)
	Below	~75 °C at 3 mm; ~30 °C at 10 mm; 25 °C at 30 mm (modes)	>182 °C at 3 mm; ~75 °C at 10 mm; ~25 °C at 30 mm (modes)	
Mixed conifer, Montana & Idaho, USA	Above	300 °C at litter surface; 515 °C at duff; 400 °C at soil surface	460-690 °C at litter surface; 400-625 °C in duff; ≤ 80 °C at soil surface	Hartford and Frandsen (1992)
	Above	429-915 °C at litter surface; 187-217 °C in duff	633-837 °C at litter surface; 69-612 °C in duff	Robichaud (1996)
	Below	37-112 °C at 22 mm; 27-86 °C at 32 mm; 13-65 °C at 47 mm	38 °C at 3 mm; 30 °C at 22 mm; 27 °C at 32 mm; 19 °C at 47 mm	
Mixed conifer forest, Idaho (ash-capped soil)	Above	20-80 °C	40-300 °C (moderate severity)	Robichaud *et al.* (2007)
	Below	40-70 °C at 10 mm; 20-60 °C at 20 mm	40-270 °C at 10 mm; 40-80 °C at 20 mm (moderate severity	
Gorse shrubland, Galicia, Spain	Above	94 °C at litter-duff interface; 37 °C at mineral soil surface	463 °C at litter-duff interface; 73 °C at mineral soil surface	Vega *et al.*(2005)
	Below	27 °C at 25mm	32 °C at 25mm	
Mixed heathland in Galicia, Spain	Above	Not measured	625 °C at litter-duff interface; 209 °C at mineral soil surface	Fernández *et al.* (2008)
	Below	Not measured	41 °C at 20 mm; 33°C at 50 mm	
Shrubland with pine, Catalonia, Spain	Above	190-200°C	> 400°C	Vadilonga *et al.* (2008)
	Below	30-40°C	40-60 °C	
Chaparral in California, USA	Above	249 °C	691 °C	DeBano *et al.* (1979) [C]
	Below	88 °C at 25 mm	199 °C at 25 mm	
	Above	Not measured	775-925 °C	Odion and Davis (2000)
	Below	Not measured	150 °C at 20 mm; 51 °C at 50 mm; 39 °C at 100 mm	
Shrubland in Portugal	Above	< 60-800 °C	< 100°C	Stoof (2011)

[A] Study compares early (low severity) and late (high severity) dry season burning; [B] directly on soil surface unless otherwise specified; [C] Data taken from stylised curves based on numerous studies in prescribed burn and wildfire areas

Table 3: Papers comparing soil water repellency for different fire severities. 0 = no change; ↑ = increase in repellency; ↓ = decrease in repellency; ↑↑ = large increase in repellency; ↓↓ = large decrease in repellency; * = change not statistically significant

Location	Strength of water repellency and change following fire					Author
	Location in soil profile of measurement	Unburnt	Fire severity			
			Low	Moderate	High	
Dry eucalypt, NSW, Australia	Surface: 0-25 mm	Strong	↓	n/a	↓↓	Doerr *et al.* (2006)
	Sub-surface: 25-50 mm	Moderate	↑	n/a	↑↑	
Mixed conifer, Idaho, USA (ash-capped soil)	Surface: 0mm	Mostly strong	n/a	n/a	↓↓	Robichaud *et al.* (2007)
	Sub-surface: 20 mm	Mostly non-repellent	n/a	n/a	↑↑	
Mixed conifer, Montana & Idaho, USA	Surface: 0 mm	Non-repellent	0	n/a	↑*	Robichaud (2000)
Ponderosa and lodgepole pine, Colorado, USA	Surface: 0 mm	Very weak	↑*	↑[A]	↑	Huffman *et al.* (2001)
	Sub-surface: 30-60 mm	Non-repellent	↑*	↑	↑	
Shrubland with pine, Catalonia, Spain	Surface: 0-25 mm	Non-repellent	0	n/a	↑*	Vadilonga *et al.* (2008)
Mixed conifer, Montana, USA	Surface: 0 mm	Very weak	↑*	↑	↑[B]	Woods *et al.* (2007)[C]

[A] Prescribed burn areas had stronger, more persistent water repellency than wildfire areas

[B] water repellency in high severity area less intense than in moderate severity area

[C] Only the results from Moose fire are reported here

2.4.1.2 Vegetative cover

Vegetative cover – on the soil surface and in the canopy – is closely related to fire severity, and reduced vegetative cover following fire is an important factor resulting in higher runoff and erosion rates. For example, Benavides-Solorio and MacDonald (2005) found percentage bare soil accounted for nearly two-thirds of the variability in sediment production rates between burnt, forested hillslopes in the Colorado Front Range. Similarly, Brock and DeBano (1982) measured higher sediment yields on bare compared to vegetated rainfall simulation plots for chaparral vegetation in Arizona; even moderate increases in vegetation cover dramatically reduced the sediment yield. Additionally, they found that infiltration rates were progressively less with decreasing litter cover. Johansen *et al.* (2001) found strong relationships between vegetative cover and both runoff and sediment yields during rainfall simulations in severely burnt ponderosa pine forests in New Mexico. In summarising the results of several studies, they showed that the relationship between sediment yield and bare soil approximates an exponential function with a sharp increase in sediment yields when the amount of bare soil exceeded 60-70%.

Vegetation cover affects runoff and erosion by intercepting rainfall, protecting the soil surface and creating surface roughness. Rainfall interception – in the canopy and leaf litter – means there is less water available for overland flow (DeBano *et al.* 1998; Sayer 2006; Stoof *et al.* 2011; Vega *et al.* 2005; Walsh and Voigt 1977), and overland flow takes longer to begin during a storm (Johansen *et al.* 2001; Leighton-Boyce *et al.* 2007; Pierson *et al.* 2009; Stoof *et al.* 2011). The amount of intercepted rainfall depends on the intensity and duration of the rainfall event, the type of vegetation, and the vegetation structure. In temperate forests annual interception rates are 5-35% (DeBano *et al.* 1998), while in a Portuguese shrubland, Stoof *et al.* (2012) reported an average interception rate of 49% ± 18%.

Vegetation cover (particularly surface litter) affects soil moisture, though its effects vary depending on the season and interval between rainfall events (Sayer 2006; Walsh and Voigt 1977). It can slow soil desiccation by protecting the soil from evaporation (Hulbert 1969; Sumrall *et al.* 1991) or it can keep the soil dry by intercepting moisture before it reaches the soil (Stoof *et al.* 2011). Soil moisture affects the soil's infiltration rate, and its propensity for soil water repellency (Keizer *et al.* 2008; MacDonald and Huffman 2004). Stoof *et al.* (2011) found that water repellency persisted for longer in unburnt areas during wet periods (as the soil was drier due to rainfall interception) but developed more quickly in burnt areas during dry periods (as the soil dried out more quickly due to greater solar insolation). Leaf litter also protects the soil surface from the direct impact of raindrops, which cause soil sealing and rain-splash erosion (DeBano *et al.* 1998; Larsen *et al.* 2009; Neary *et al.* 1999; Sayer 2006). Surface roughness, caused by plant litter, reduces runoff by increasing the amount of water ponding on the soil surface (Stoof *et al.* 2012) and reduces erosion by slowing runoff and thus diminishing its sediment transport capacity (DeBano *et al.* 1998).

Fire severity may affect changes in vegetation cover after burning. Soon after a burn, leaf fall from scorched shrubs and trees will increase cover on the forest floor (Prosser and Williams 1998). The amount of leaf fall depends on the fire severity, while the timing depends on the timing of windy weather following the fire (Dragovich and Morris 2002). Cerdà and Doerr (2008) found that scorched needles on the forest floor substantially reduced sediment yields compared with ‘ash only’ plots in a series of rainfall simulations 3-10 days following a fire in eastern Spain. Pannkuk and Robichaud (2003) investigated the effect of needle type on post-fire erosion and found that long needles (ponderosa pine) were more effective at reducing rill erosion while short needles (Douglas fir) were more effective at reducing interrill erosion. Rates of vegetation recovery are influenced by a number of factors including fire severity, the climatic conditions during the post-fire period and the vegetative type. Benavides-Solorio and MacDonald (2005) reported substantially less bare soil for low fire severity plots compared to high and moderate fire severity plots six years after fire in the Colorado Front Range. Larsen et *al.* (2009) reported an average surface cover of 58% five years after high severity fire in the Colorado Front Range, which was 20% less cover than in unburnt areas. Prosser and Williams (1998) reported that vegetation had not fully recovered two years after a moderate severity fire in the forested sandstone region near Sydney, Australia.

2.4.2 **Burn patchiness**

In a prescribed burn, different fire severities and unburnt areas create a mosaic of patches (Figure 4). Fire severities are often higher on the ridges and drier aspects and lower (or unburnt) in the gullies and on wetter aspects (Bradstock *et al.* 2010; Penman *et al.* 2007; Pettit and Naiman 2007). At finer spatial scales – within a fire severity patch – spatially variable hydrologic properties are caused by various spatial distributions of water repellency (Ferreira *et al.* 2008; Woods *et al.* 2007), macropores (Beven and Germann 1982) and bioturbation (Garkaklis *et al.* 1998). This patchiness may influence hydrologic connectivity – a measure of how effectively runoff and erosion producing areas (active areas) connect to catchment outlets (Ambroise 2004). Hydrologic connectivity is increasingly seen as central to understanding runoff and erosion processes in patchy environments (see reviews by Bracken and Croke 2007; Ferreira *et al.* 2008; Michaelides and Chappell 2009; Pringle 2003).

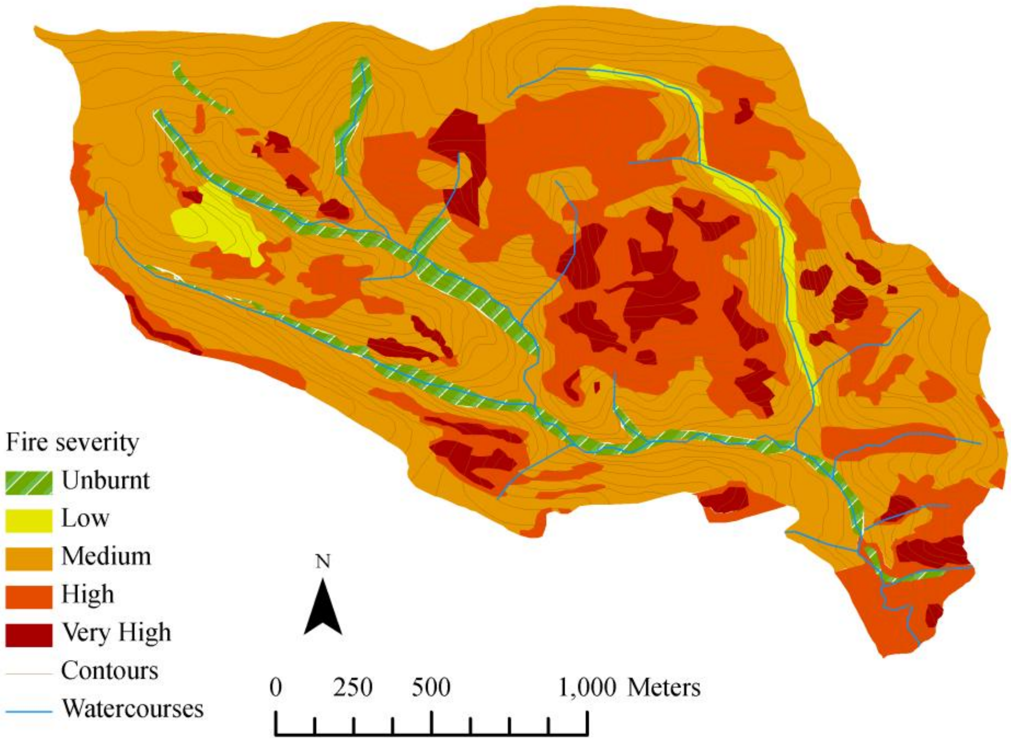


Figure 4: An example of a typical prescribed burn in Victoria, Australia (this burn was conducted in Autumn 2005 in the Otway Ranges). The map shows a mosaic of fire severities. Very high = complete crown scorch; high = partial crown scorch; medium = understorey completely burn, crown not scorched; low = understorey partially burnt. The patchiness was created by ignition patterns, topography and fuel moisture differences. The severities were mapped using aerial photographs taken 6-weeks post-burn and validated by field surveys. The data were provided by the Department of Sustainability and Environment.

Although there has been little research about hydrologic connectivity in burnt environments, much can be learnt from patchy vegetated environments – e.g. tropical savannas and semi-arid shrublands – which are the focus of numerous studies. In these environments, the vegetated patches act as sediment sinks and the bare patches act as sediment sources (Cerdà 1997; Mayor *et al.* 2009; Reid *et al.* 1999). Yet, a simple tally of area for each patch type is a poor predictor of catchment sediment yields because the spatial arrangement of the patches is also important (Boer and Puigdefábregas 2005; Ludwig *et al.* 2007). For example, Bartley *et al.* (2006) measured large differences in runoff volume (runoff ratios of 8% versus 71%) for plots with similar average vegetation cover but different spatial arrangements of cover.

One important feature of the spatial arrangement of patches is the proximity of bare patches to the catchment outlet (Bartley *et al.* 2006; Reaney 2003). Runoff and sediment yields are greater for plots where bare patches are located at the bottom of the plot. For example, Bartley *et al.* (2006) found that a plot producing most runoff had a large bare patch near its outlet. Even narrow vegetated patches can be highly effective at trapping runoff and sediment. For example, Reaney (2003) predicted that a five metre vegetated strip at the bottom of a hillslope would prevent any runoff from connecting to the hillslope outlet (for simulated 75 mm h^{-1} storms lasting five minutes).

Another important factor is patch density (i.e. the size of patches) (Figure 5). Bautista *et al.* (2007) measured runoff in plots with variable patch densities and found that a plot with the lowest patch density (i.e. larger patches) had five times more runoff and six times more sediment than one with the highest patch density (i.e. smaller patches). Similarly Boer and Puigdefábregas (2005) predicted higher rates of discharge and soil loss from hillslopes with low patch densities. Reaney (2003) reported a slightly different relationship based on multiple model simulations with different densities and patch arrangements. He found that hillslopes with the same vegetation cover had similar mean runoff coefficients regardless of patch density, but for the lower patch densities the standard deviation was larger. Thus low patch densities produced both the highest and the lowest runoff coefficients – the highest runoff coefficients occurred where large patches of bare soil were at the bottom of a hillslope and the lowest runoff coefficients occurred where large patches of vegetation were at the bottom of a hillslope.

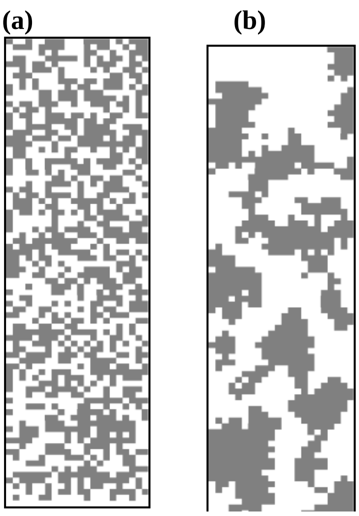


Figure 5: Examples of (a) high density and (b) low density patchiness.

If burnt landscapes were similar to patchy vegetated environments, then we would expect burnt areas to act as sediment sources and unburnt areas to act as sediment sinks. Though there is little research about this, some authors acknowledge its potential significance (e.g. Benavides-Solorio and MacDonald 2005; Ferreira *et al.* 2008; Kutiel *et al.* 1995; Smith *et al.* 2010). In North American sagebrush, burning reduced the landscape's patchiness and thus increased runoff connectivity (Pierson *et al.* 2009; Pierson *et al.* 2008; Pierson *et al.* 2001). Sagebrush is typically patchy with coppice micro-sites acting as sediment sinks; burning reduced the infiltration rates and surface roughness in those micro-sites, which led to increased runoff connectivity. Robichaud and Monroe (1997) used the Water Erosion Prediction Project (WEPP) model to simulate the amount of sediment leaving a hillslope for various spatial sequences of fire severity; both the low and high severity patches acted as sediment sources. Interestingly, the sequence with high fire severity upslope of low fire severity generated more sediment than the reverse arrangement because run-on from the high fire severity patch increased the amount of erosion in the low fire severity patch. Moody *et al.* (2008) incorporated both the magnitude of fire severities and their spatial arrangement along flow paths into a catchment scale index – 'hydraulic functional connectivity'. This index was linearly related to catchment runoff.

The influence of spatial variability on runoff connectivity has been studied more at finer spatial scales (centimetres to metres) than coarser spatial scales (metres to decimetres), but still remains poorly understood. The research at finer spatial scales mostly relates to preferential pathways for infiltration caused by wettable patches, macropores, cracks, stones and bioturbation in otherwise water repellent soil (Doerr *et al.* 2003; Doerr and Moody 2004; Ferreira *et al.* 2008; Ferreira *et al.* 2009; Shakesby *et al.* 2000; Urbanek and Shakesby 2009). The influence of those preferential pathways is thought to be very significant at larger spatial scales, resulting in limited runoff connectivity despite widespread water repellency (Doerr *et al.* 2003; Shakesby *et al.* 2000). The prevalence of wettable, infiltrating patches following fire may be related to the fire severity (Ferreira *et al.* 2005; Ferreira *et al.* 2008; Ferreira *et al.* 2009). Woods *et al.* (2007) found larger patches of water repellent soil in high and moderate fire severity areas compared to low fire severity areas. Ferreira *et al.* (2005) found there was greater variability in overland flow for lower fire severity prescribed burnt soils (with spatially variable water repellency) than higher fire severity wildfire burnt soils (with more uniform water repellency). For soils with uniform water repellency runoff connectivity may be interrupted by macropores (Doerr *et al.* 2003; Nyman *et al.* 2010a; Sheridan *et al.* 2007). Nyman *et al.* (2010a) found that macropores accounted for 70% the soil's field-saturated conductivity despite comprising only 5.5% of the soil volume in a burnt, wet eucalypt forest. Previously at the same site, Sheridan *et al.* (2007) found that the connected length for infiltration-excess overland flow on water repellent soil was only a few metres due to spatially variable saturated conductivity. While macropores may be an important pathway for infiltration in some burnt locations, the exposed soil surface following fire makes the soil more prone to sealing, which reduces their importance in other locations (Larsen *et al.* 2009; Onda *et al.* 2008). Bioturbation and burnt-out roots also create pathways for preferential flow in burnt soils (Ferreira *et al.* 2008; Garkaklis *et al.* 1998; Shakesby *et al.* 2007). Dragovich and Morris (2002) in the Sydney sandstone area, found rates of bioturbation were higher in moderate fire severity areas compared with high fire severity areas. Stones are another source of preferential flow in water repellent soils, as water is able to infiltrate along the soil-stone interfaces – Urbanek and Shakesby (2009) found that the rate of infiltration increased with increasing stone content in sandy, water repellent soil.

2.4.3 **Burning season**

Most prescribed burns are conducted under mild weather conditions when the fuels are relatively moist (but still dry enough to burn). This equates to autumn or spring burning in temperate climates and early dry season burning in tropical climates. Seasonal differences in the moisture content of fuels and soil between spring and autumn may be important to post-fire runoff and erosion as pre-burn fuel moisture contents affect the extent of soil heating (Robichaud *et al.* 2007; Robichaud and Waldrop 1994). For example, in a ponderosa pine forest, Hatten *et al.* (2008) measured less soil organic matter for soils burnt in autumn compared with spring, which suggests that the residual dryness in the soil following summer resulted in more soil heating and greater consumption of organic matter. Ronan (1986) recommended spring over autumn burning because the relatively moist soils in spring were likely to inhibit soil heating. In tropical regions, prescribed burning is encouraged early in the dry season, when the fuels and soils are relatively moist (Russell-Smith and Edwards 2006). In northern Australia Townsend and Douglas (2000) compared runoff and erosion from sites burnt early and late in the dry season and found that the late season burn caused more runoff and erosion, which they concluded was partially due to the higher fire severity and lower patchiness of the late season burn. The other important factor identified by Townsend and Douglas (2000) was the time-lag between burning and post-fire rainfall. With less time to recover before the monsoon, the late dry season burns were more susceptible to post-fire runoff and erosion (Townsend and Douglas 2000). In temperate regions, more rain tends to occur in winter – soon after the autumn burning season – but the most intense, erosive storms are often in summer. Since intense storms usually cause the most significant runoff and erosion (Smith *et al.* 2011c), these seasonal differences in rainfall intensity suggest that spring burns are most susceptible to post-fire erosion in temperate climates, as there is less time for recovery before the most erosive storms are likely to occur.

2.4.4 **Fire frequency**

Most research about fire effects on runoff and erosion consider individual burns as isolated ecosystem disturbances; thus little is known about the effect of repeated burning or fire frequency. Exceptions include a series of studies done at Mt Carmel in Israel that considered the effect of different fire frequencies on vegetation recovery, runoff and erosion (Wittenberg and Inbar 2009; Wittenberg *et al.* 2007). These studies found that recurrent burning increased the length of recovery for vegetation, leaving the soil susceptible to erosion for longer periods. In shrubland in Valencia, Spain, Campo *et al.* (2006) reported higher runoff and erosion rates for plots burnt twice, though this was probably due to higher rainfall intensities and the timing of post-fire rainfall during the study rather than the double-burn treatment. In eucalypt forest in south-eastern Australia, repeated low-intensity fire caused changes to vegetation structure and composition (Tolhurst 2003; Tolhurst and Kelly 2003) and reduced soil organic matter (Hopmans 2003). Lastly, in a review about the cumulative effects of fuel treatments in western North America, Elliot *et al.* (2010) highlighted the need to consider the implications of multiple management actions at larger spatial scales and longer temporal scales.

The most visible effects of frequent burning in the same location are changes to vegetation structure and composition. Frequent fires often lead to a more open forest understorey (Close *et al.* 2009; Jurskis *et al.* 2003; Ribe 2006; van Wagtendonk 2006) and some plant species are favoured by frequent fire, such as grasses (White *et al.* 2006) or bracken fern (*Pteridium esculentum*) (Tolhurst 2003). Those changes to vegetation structure and composition may have implications for runoff and erosion because some plant species and vegetation structures are more effective at reducing runoff and erosion than others (Cerdà and Doerr 2005; Walsh and Voigt 1977; White *et al.* 2006). For example, Cerdà and Doerr (2005) found that herbs and shrubs were more effective at reducing erosion rates than trees and dwarf shrubs. Dense vegetation structures with deep layers of organic matter (associated with infrequent fire) are likely to be less susceptible to runoff and erosion due to higher interception rates. However, while there may be less runoff and erosion during the inter-fire period, when fires occur they are likely to be more intense due to the larger amount of fuel in this sort of vegetation cover.

Other effects of frequent burning in the same location include the loss of organic matter and root biomass in the soil. In a mixed-eucalypt foothill forest Hopmans (2003) found that prescribed burning every three years (from 1985 to 1998) was associated with a 14% decline in soil carbon (to a depth of 2 cm) while burning every 10 years showed no decline. Higher losses of soil carbon occurred at sites that burnt more intensely, while the loss of soil carbon was negligible for sites that burnt less intensely. Fine roots are important for binding soil surface materials and reducing erosion (Gould 1998; Gyssels *et al.* 2005). In a ponderosa pine forest, Hart *et al.* (2005) found that fine root and mycorrhizal root biomass decreased over 20 years of burning at two year intervals compared with an unburnt control.

Often prescribed burning programs involve burning different sections of the same catchment over several years. Impacts on water quality from erosion within each individual burn area may be small due to the size of the burns relative to the catchment area, the location of the burns within the catchment and other factors discussed throughout this chapter. However, the effects of multiple burns may be more substantial if the sediment from several burnt areas accumulates downstream; this is referred to as a serial cumulative effect (Luce and Rieman 2010). Furthermore, burning different sections of the same catchment over several years may result in elevated constituent concentrations for prolonged periods, as there is always a recently burnt section of the catchment contributing sediment. These burning practices may also create a constant (albeit low) possibility of a substantial water quality impact should an intense storm occur in a recently burnt area. In contrast, catchments which are only burnt by infrequent wildfires will experience prolonged periods with no fire-related water quality impacts.

2.5 The interaction between fire regimes and rainfall

While the fire regime is extremely important in accounting for post-fire runoff and erosion, the magnitude of any impact is determined by the interaction of a combination of factors – e.g. slope, aspect, flow convergence, vegetation type, soil type, geology and rainfall properties. The fire regime affects the threshold of those other factors above which high magnitude runoff and erosion occur. The conceptual model in Figure 6 illustrates how fire severity and rainfall intensity may interact to generate different hydrological responses (Neary *et al.* 1999). The same rainfall intensity will generate different amounts of runoff depending on the fire severity, and the same fire severity will generate different amounts of runoff depending on the rainfall intensity. This model provides an explanation for the large variability in post-fire runoff and erosion rates often observed for areas burnt with similar fire severities (Smith *et al.* 2011c). Rainfall properties are also likely to interact with burn patchiness to produce particular hydrologic responses. For example, in semi-arid environments, patchiness most affects runoff connectivity during moderate intensity storms (e.g. Boer and Puigdefábregas 2005; Puigdefábregas 2005) when there is enough rain to generate runoff in bare patches but not in vegetated patches. Conversely, during intense storms vegetated and bare patches generate runoff at similar rates while during low intensity storms neither patch type generates runoff.

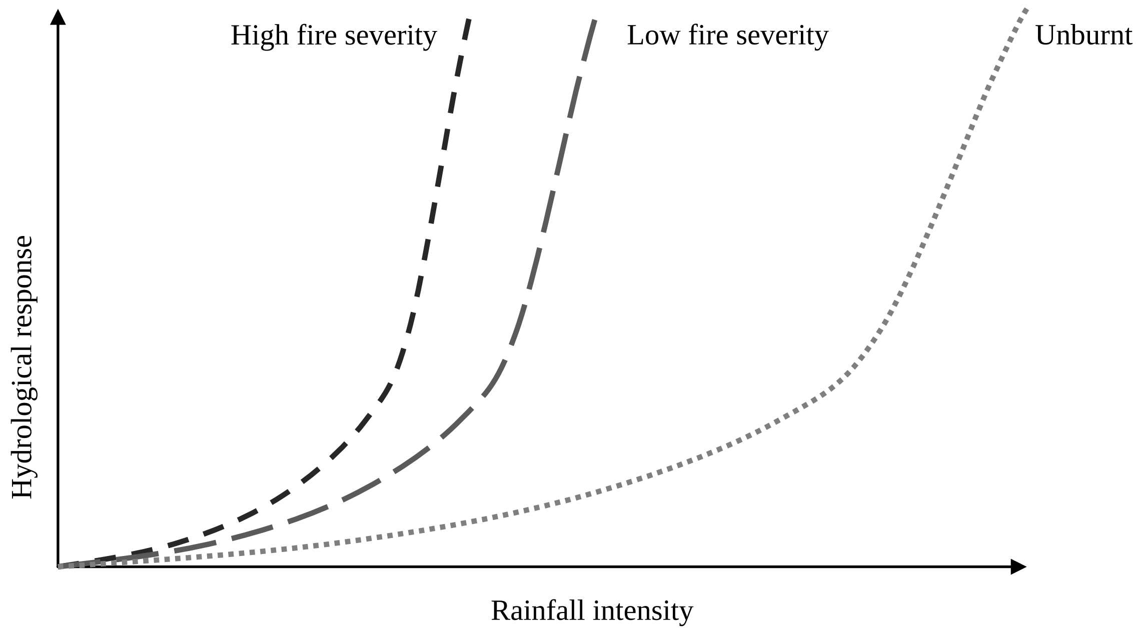


Figure 6: Conceptual model of the interactive effect of rainfall intensity and fire severity on post-fire runoff and erosion. Model assumes that other factors, such as vegetation type, soil type and geology are constant.

2.6 Research gaps

Further research into the effects of prescribed burning on runoff and erosion is required because significant knowledge gaps remain in relation to the factors controlling particular post-fire hydrologic and erosion responses, quantifying the likelihood of large impacts, understanding the effects of spatial scale on the magnitude of an impact and quantifying the long-term risks of repeated burning. Two types of research are required: (1) process-based studies to understand the factors (e.g. fire regime characteristics) controlling surface runoff and erosion, and (2) landscape-scale surveys to quantify the frequency and magnitude of large erosion events.

The processes-based studies should seek to:

- relate fire severity measures to soil heating and changes to soil hydrologic properties
- understand how hydrologic and erosion processes at small spatial scales manifest themselves at larger spatial scales, especially during high magnitude events
- understand how soil water repellency affects surface runoff and erosion at larger spatial scales, and to quantify its importance, relative to the loss of vegetative cover and soil sealing

- examine the hydrologic effects of patchiness in burnt landscapes, and to develop methods to quantify patchiness
- define the so called ‘window of disturbance’ (i.e. length of time over which an area has an increased susceptibility to runoff and erosion following fire) particularly in relation to vegetation recovery for different fire severities and magnitude storms
- understand the effects of repeated burning in the same location and in different parts of the same catchment.

The landscape-scale surveys should involve observation of a large number of prescribed burnt catchments to quantify the frequency of high magnitude erosion. More detailed post-hoc surveys of the locations identified to have high magnitude erosion could be undertaken to quantify the severity of the erosion and the thresholds required to generate those large impacts. This information would be useful for catchment managers who need to predict the likelihood of large impacts following prescribed burning.

Both research approaches should contribute to the development of management tools that enable a more systematic analysis of the risks associated with prescribed burning in particular locations. These tools could be used to locate prescribed burns in areas that pose the least risk to water quality, guide the operational management of the burn (e.g. ignition patterns) and identify areas with the highest risk of surface runoff and erosion post-burn.

3. Research design and site description

This chapter describes a conceptual model of how fire severity and burn patchiness are perceived to influence post-fire runoff and erosion following prescribed burning. It then introduces a shortlist of hypotheses based on the conceptual model and the broad methods used to test them. Finally, the chapter describes the three study sites – Upper Yarra, Big Ben and Mt Cole.

3.1 Introduction

In the previous chapter (Chapter 2) two important directions for future research about the effects of prescribed burning on runoff and erosion were identified: (1) process-based studies to understand the factors controlling surface runoff and erosion, and (2) landscape-scale surveys to quantify large erosion events. This thesis addresses the first of those research directions by examining the effects of the fire regime on soil properties, surface runoff and erosion in dry eucalypt forests. The fire regime is an important factor distinguishing prescribed burns from severe wildfires, and it can be manipulated by land managers, which means research findings could be used to improve burning practices.

There are several examples where prescribed burns have had little impact on water quality at the catchment-scale (e.g. Arkle and Pilliod 2010; Elliot and Vose 2005; Galang *et al.* 2010; Richter *et al.* 1982; Smith *et al.* 2010). Researchers sometimes attribute those low impacts to the low fire severity (e.g. Arkle and Pilliod 2010; Richter *et al.* 1982) or the high degree of burn patchiness (e.g. Richter *et al.* 1982; Smith *et al.* 2010); however, there is limited literature available to support those inferences (as discussed in Chapter 2). This thesis addresses this knowledge gap by examining the effects of fire severity and burn patchiness on runoff and erosion properties and processes. Fire severity is a qualitative measure of changes to organic matter as a result of fire (Keeley 2009). It encapsulates the amount of scorched, burnt and unburnt vegetation in each vegetation strata (e.g. Chafer 2008; Edwards *et al.* 2003; Parsons 2003). Burn patchiness represents the mosaic of fire severity patches resulting from a prescribed burn (Penman *et al.* 2007) (Figure 4 in Chapter 2). The combination of fire severity and burn patchiness was chosen as the focus of this thesis (as opposed to other fire regime characteristics) because they occur at similar spatial and temporal scales and existing literature suggests they play an important role in post-fire runoff and erosion (e.g. Benavides-Solorio and MacDonald 2005; Moody *et al.* 2008; Robichaud and Monroe 1997).

The purpose of this chapter is to explain the link between the existing literature and the research conducted for this thesis. Firstly, a conceptual model of the system based on the literature review is outlined. This model forms the basis for a shortlist of hypotheses, which are presented. The methods used to test those hypotheses are then introduced (specific details about methods are presented in the results chapters). Finally, the study sites are described in terms of their location, climate, vegetation, soils, fire history and the burn treatments applied during the study.

3.2 Conceptual model

The conceptual model proposes that the volume of hillslope-derived surface runoff and erosion entering a stream following a prescribed burn depends on: (1) hydrological and erosional processes occurring within patches, which vary as a function of the fire severity, and (2) the spatial interaction between those patches (Figure 7). Basic premises of the model are that:

- Prescribed burning results in a mosaic of unburnt, low and high fire severity patches (Penman *et al.* 2007) (Figure 4 in Chapter 2).
- Burnt patches produce more runoff and erosion than unburnt patches (as reviewed by Certini 2005; Shakesby 2011; Shakesby and Doerr 2006; Shakesby *et al.* 2007).
- The runoff and erosion producing potential of a burnt patch depends on the fire severity (as demonstrated by Benavides-Solorio and MacDonald 2001; Dragovich and Morris 2002; Robichaud 2000).
- The amount of runoff and eroded sediment connecting to a point on the hillslope depends on the type, size and spatial arrangement of patches upslope of that point (as demonstrated by Moody *et al.* 2008; Robichaud and Monroe 1997).

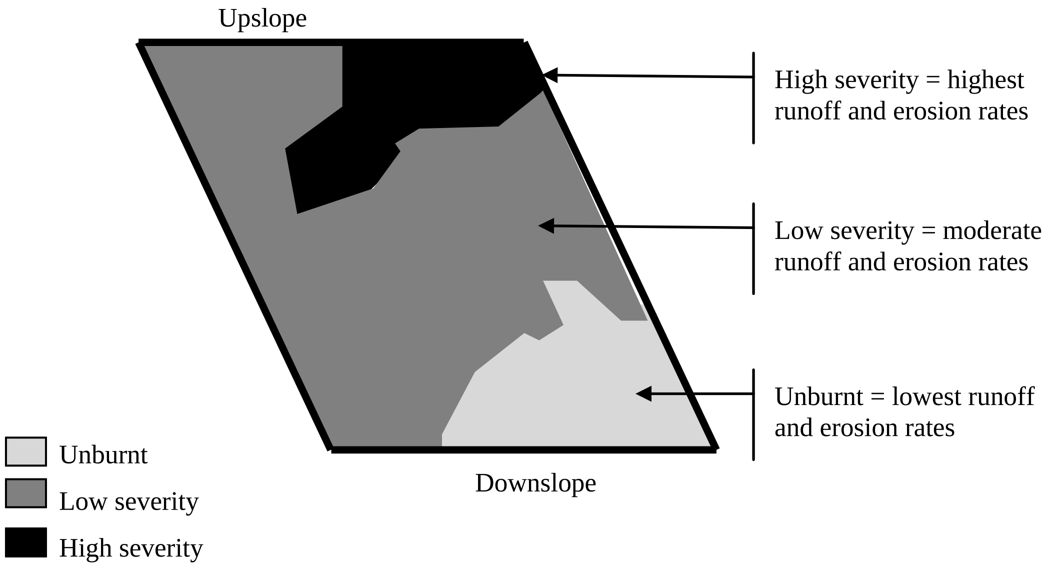


Figure 7: A hypothetical prescribed burnt hillslope with spatially variable fire severities and unburnt patches. The hydrologic and erosion properties and processes differ within each patch type resulting in some patches acting as sediment sources and others acting as sediment sinks. The amount of runoff and erosion reaching the bottom of the hillslope depends on the hydrologic and erosion processes occurring within the patches and their spatial arrangement.

3.3 Properties and processes within patches

The first part of the conceptual model is concerned with the hydrologic and erosion processes occurring within unburnt, low severity and high severity patches. Figure 8 (based on the literature discussed in Chapter 2) illustrates how burning is expected to affect runoff and erosion.

Fire severity is shown to directly affect vegetative cover and soil water repellency, and indirectly affect runoff and erosion (as discussed by Benavides-Solorio and MacDonald 2001; Doerr *et al.* 2006; Dragovich and Morris 2002; Robichaud 2000). As vegetation cover diminishes – with increasing fire severity – there is less rainfall intercepted, resulting in larger volumes of water reaching the soil surface to potentially become surface runoff (Sayer 2006; Vega *et al.* 2005; Walsh and Voigt 1977). The loss of vegetation cover also exposes the soil to raindrop impact, which can reduce infiltration capacities through soil sealing and increase rain-splash erosion rates (DeBano *et al.* 1998; Larsen *et al.* 2009). Furthermore, the loss of vegetation cover means that surface roughness is reduced, which leads to increased hydraulic forces (e.g. higher runoff velocities and shear stress) and increased sediment transport capacity (DeBano *et al.* 1998). Soil water repellency has been found to increase with increasing fire severity in some studies (Robichaud 2000; Vadilonga *et al.* 2008; Woods *et al.* 2007) while other studies report a reduction in surface soil water repellency in high severity areas coupled with its intensification lower in the soil profile (Doerr *et al.* 2006; Robichaud *et al.* 2007). In both instances the altered water repellency can reduce infiltration capacities and enhance either rain-splash erosion (where surface water repellency is enhanced) (DeBano 2000; DeBano *et al.* 2008; Terry and Shakesby 1993) or rill erosion (where surface repellency is reduced but subsurface repellency is enhanced) (Doerr *et al.* 2006) .

The extent to which runoff and erosion rates differ between the fire severity patches is also likely to vary as a function of other site characteristics, such as slope gradient, soil type, aspect and vegetation type. These factors are not included in the conceptual model as they are independent of fire severity and burn patchiness (at least over the temporal scales investigated for this study). Consequently, they have been controlled in the study.

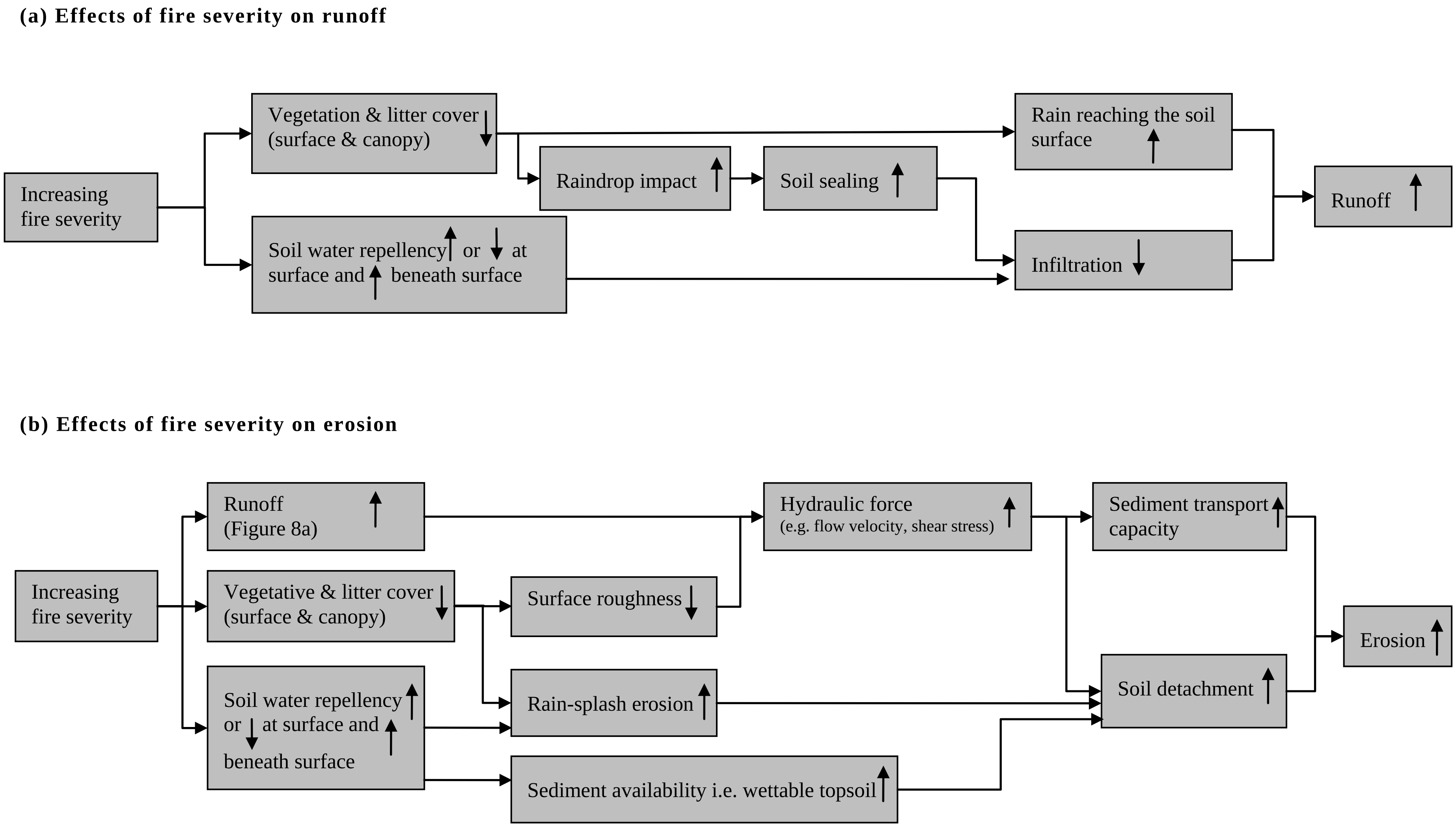


Figure 8: Conceptual diagrams showing the effects of fire severity on (a) runoff and (b) erosion. Arrows within the boxes show the expected change to that property or process as a result of increasing the fire severity.

3.4 The spatial interaction between patches

The second component of the conceptual model considers the spatial interaction between fire severity patches at the hillslope-scale. Figure 9 provides some examples of how patch type, patch arrangement and patch size are expected to affect the amount of sediment and runoff connecting to a particular point on the hillslope. The size of the bars signifies the relative amounts of runoff and erosion at a particular point on the hillslope. The first series of hillslopes show that high severity patches are expected to generate the most runoff and erosion and unburnt patches the least. This expectation is based on the relationships between fire severity, runoff and erosion described above (Figure 8).

The second series of hillslopes show that when there is more than one fire severity patch type on a hillslope, the connectivity of runoff / erosion is affected by the spatial arrangement of these patches (Moody *et al.* 2008; Robichaud and Monroe 1997). The model predicts that unburnt patches are effective at reducing runoff and erosion from upslope areas, while burnt patches are less effective, or have no reducing effect.

The third series of hillslopes show the effect of patch size. Larger high severity patches generate more runoff / erosion than smaller high severity patches, and larger unburnt patches reduce the connectivity of runoff / erosion more effectively than smaller unburnt patches. However, there are likely to be upper limits to the amount of runoff / erosion generated or reduced, and hence patch size is only important for patches up to a certain size.

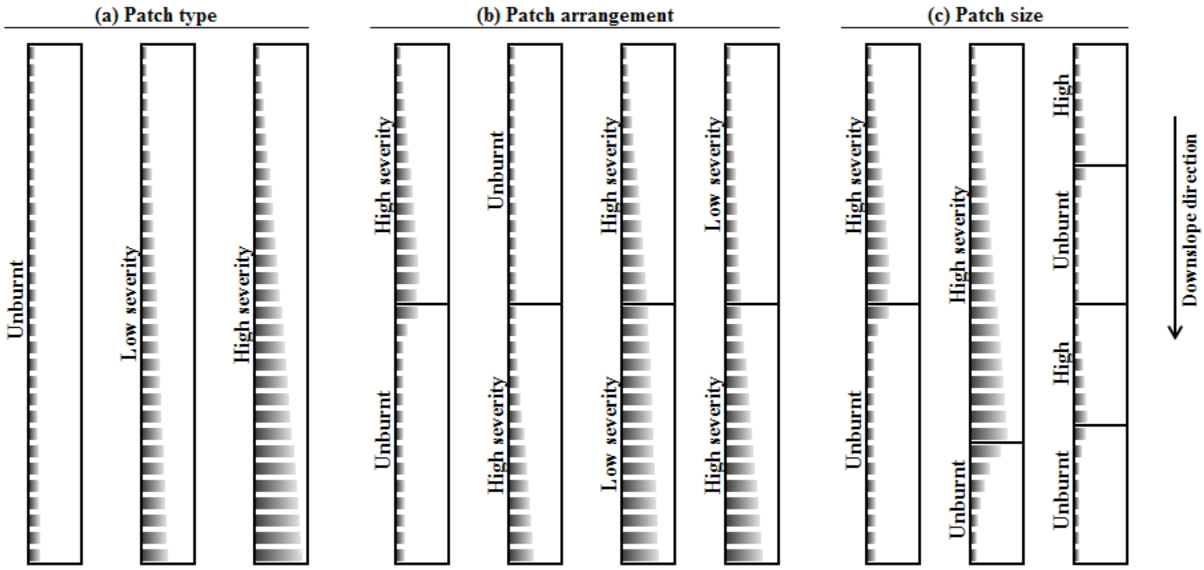


Figure 9: Selected examples to illustrate the potential effects of patch type, size and arrangement on runoff and erosion connectivity along hillslope flow paths. The diagram depicts hillslope sections (or flowpaths) with different patch arrangements and patch sizes. The bars represent the relative volume of runoff and erosion reaching different points on the hillslope.

3.5 Hypotheses to be tested

The hypotheses developed in this thesis are designed to test the basic premises of the conceptual model at several spatial scales. They consider the effects of burning (burnt versus unburnt), fire severity (low versus high severity) and burn patchiness. They are presented in Figure 10 in a hierarchal order based on their spatial scale of interest. The overarching hypothesis (Hypothesis E), which integrates the effects of burning, fire severity and patchiness at the hillslope-scale, is at the top of the hierarchy.

There are several hypotheses about post-fire recovery, which anticipate that full recovery to pre-fire runoff and erosion patterns will occur within 18-months of burning. This time-frame was chosen primarily because it was the maximum length of time that could be spent collecting data within the time-frame of the study. However, the 18-month time-frame is not dissimilar to recovery periods observed in some other Australian studies – e.g. 12-18 months (Smith *et al.* 2010), two years (Sheridan *et al.* 2007) and one year for a low intensity burn (Ronan 1986). Figure 10 also shows the chapters where each of the hypotheses are addressed. Each hypothesis is addressed within the bounds of the study site and rainfall conditions during the measurement period.

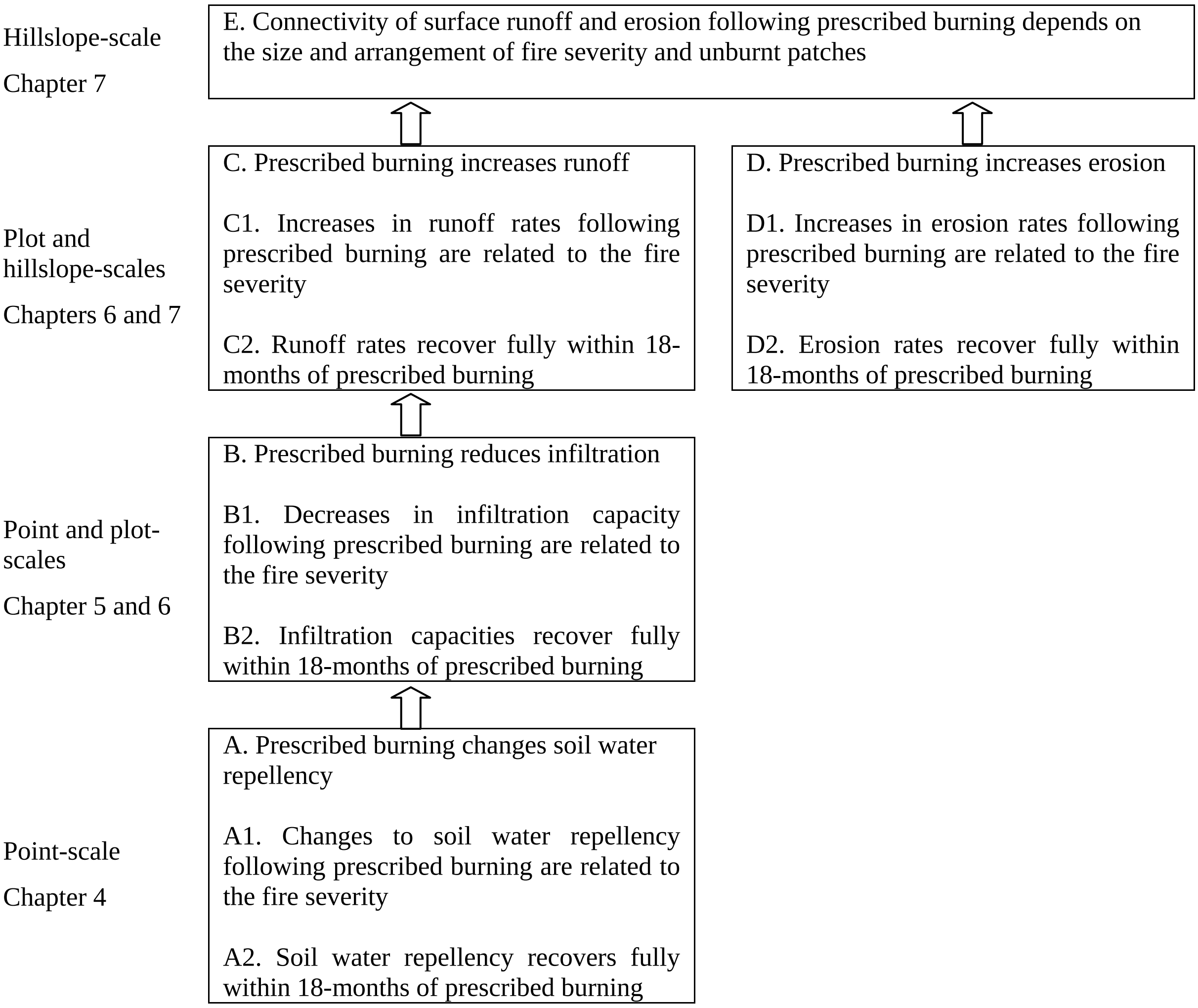


Figure 10: Hierarchy of research hypotheses addressed in this study, the spatial scales at which they are addressed and the corresponding results chapters where the data are presented.

3.6 Methodology

3.6.1 Study site selection

The study involved the application of prescribed burning to forest sites. Owing to the many logistical constraints associated with prescribed burning, field measurements were undertaken at three study sites (Upper Yarra, Big Ben and Mt Cole – Figure 11) to increase the likelihood of achieving a desirable burn outcome at least once during the study period. Also, the three sites provided insights into differences in the post-fire response between variants of dry eucalypt forest (Department of Sustainability and Environment 2011c). The following factors were considered during site selection:

- likelihood of being burnt – the sites were within proposed prescribed burns for the upcoming burn season and fire managers identified them as being the most likely sites to be burnt
- vegetation type – only sites with dry eucalypt forest were selected
- soil type – the sites were deliberately chosen to have contrasting soil types (i.e. clay loam versus sandy soils) so that they could be used to provide insights into differences in the post-fire response between variants of dry eucalypt forest
- accessibility – the sites needed to be accessible throughout the year for fieldwork
- security – the sites needed to be reasonably inaccessible to the general public.

The burns were successful at all three sites, and hence post-fire measurements were conducted at all three sites. However, fewer measurements were done at Mt Cole and Big Ben compared to Upper Yarra due to time and resource constraints. The Upper Yarra site was chosen for the most intensive sampling because it was the most accessible, was burnt in the first year of the study and contained a range of fire severities and unburnt areas within which to sample. Table 4 provides some details about each of the burns.

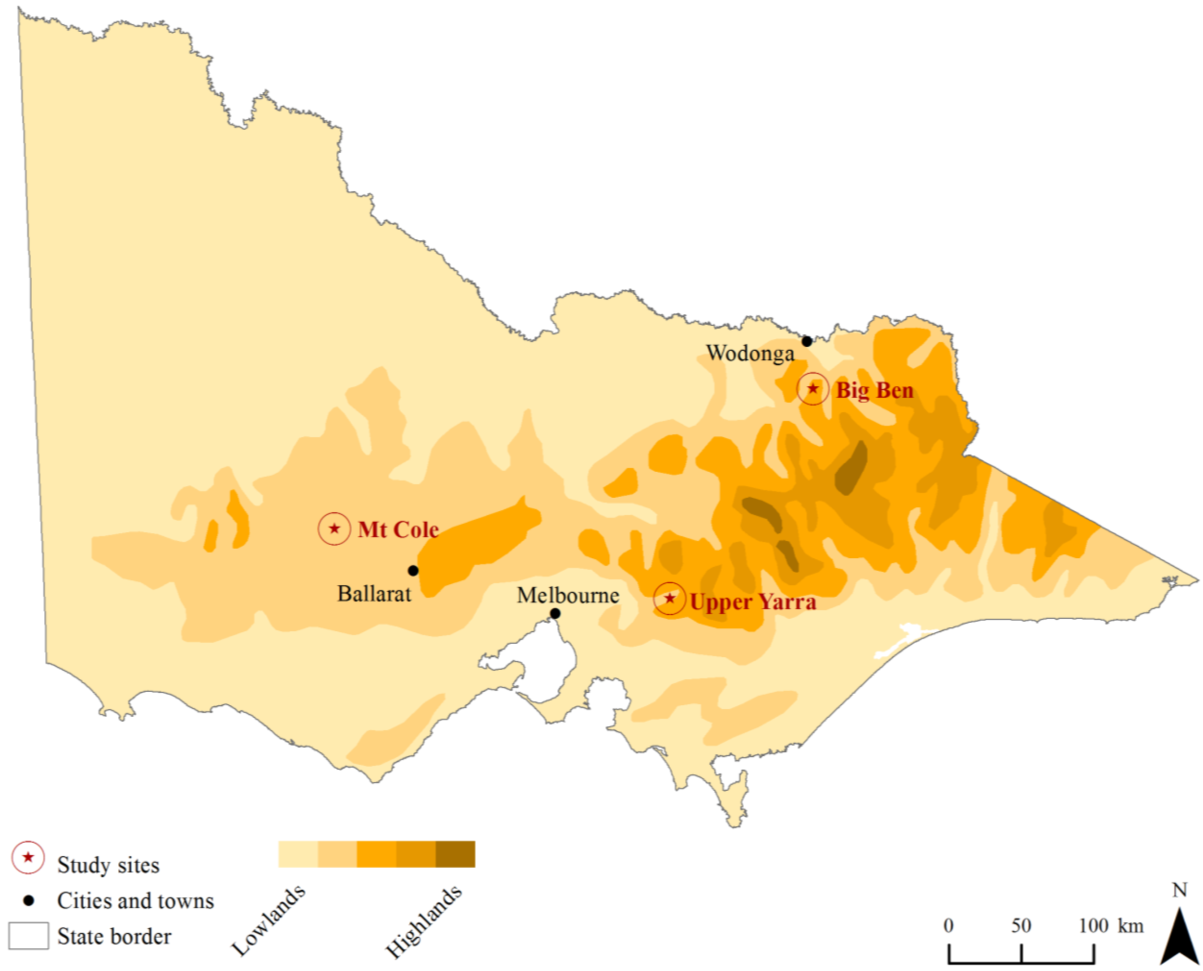


Figure 11: Location of the study sites within Victoria, Australia

Table 4: Details about the burns at each study site.

Study site	Burn name & number	Burn ignition start date	Plot ignition date(s)	Burn size (ha)	Land management objective
Upper Yarra	Smoko Ridge (P107)	20/4/2009	21/4/2009 22/4/2009	1384	Develop a strategic fuel reduced area of sufficient width and continuity to provide a substantial barrier to the spread of bushfires.
Big Ben	Big Ben (S147)	19/4/2009	21/4/2009	5569	To provide an irregular mosaic of areas of fuel reduction to complement works in adjacent fuel management zones.
Mt Cole	Manly Point (10BE01)	13/3/2010	15/3/2012	228	To develop fuel reduced areas of sufficient width and continuity to reduce the spread of wildfires.

3.6.2 **Treatment plots**

A major component of the study was a series of treatment plots (15 m x 50 m) established at each site prior to burning (Figure 12). A block design was used to isolate treatment effects from other potential confounding variables such as differences in slope or aspect, although the blocks were chosen to be as similar as possible within a site. There were three plots within each block and each was assigned a different burn treatment (unburnt, low fire severity and high fire severity) (Table 5). Different ignition patterns were used to achieve the burn treatments (Table 6). The steepest plot with the greatest fuel hazard (McCarthy *et al.* 1999) was assigned to the high fire severity treatment, while the plot with the lowest fuel hazard was retained as unburnt.

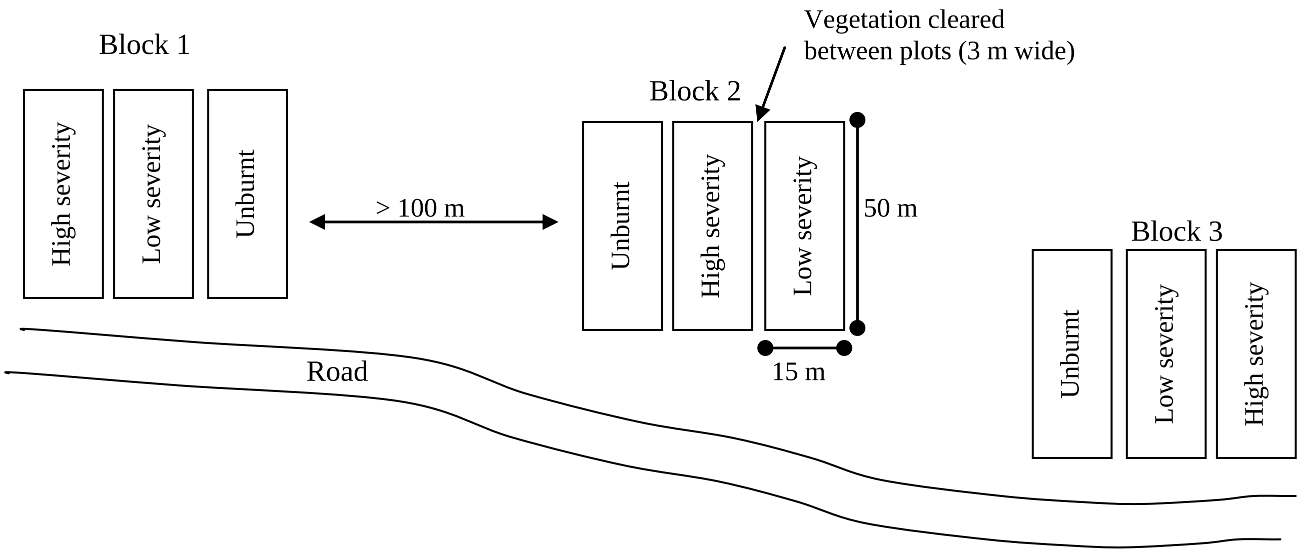


Figure 12: Original sampling design. A block design was intended to be used with burn treatments (unburnt, low severity and high severity) assigned to plots (15 m x 50 m) within blocks.

Table 5: Original sampling design at each study site

	Site 1 (Upper Yarra)	Site 2 (Big Ben)	Site 3 (Mt Cole)
No. of blocks	3	3	3
No. of plots per block	3	3	3
Treatments in each plot	Unburnt Low severity High severity	Unburnt Low severity High severity	Unburnt Low severity High severity
Total no. of plots	9	9	9
No. of sample points per plot[A]	9	8	8
Total no. of points	81	72	72

[A] There were eight or nine points per plot depending on the transect layout.

Table 6: Ignition patterns and fire severity definitions

Treatment	Lighting patterns	Intended fire severity outcome
Unburnt	Fire excluded	Plots unburnt
Low severity	Ignite with spots or strips upslope of the plot to create a backing fire	Burnt and unburnt surface fuels; scorched or unburnt shrub layer; intact canopy
High severity	Ignite with spots or strips downslope of the plot to create a head fire	Completely burnt surface fuels; completely burnt shrub layer; completely scorched canopy

The low severity and unburnt treatments within the plots were successfully achieved in most instances. However, the fire intensities were usually insufficient to achieve the high fire severity treatments within the designated plots. The final result was more low fire severity plots than originally planned (usually two per block), a sufficient number of unburnt plots, and very few high fire severity plots. To compensate for the shortage of high fire severity plots, additional plots were established in other parts of the prescribed burn. Table 7 outlines the final sampling design. Sometimes locations for new high severity plots could not be found, resulting in an unbalanced number of plots per treatment. At Mt Cole, no high fire severity areas could be found within the prescribed burn.

Soil temperature, water repellency, vegetation cover, infiltration capacity and soil moisture were measured at points within each plot at various times before, during and after the burns. Table 7 and Figure 13 show the number of points in each block and their layout, while Table 8 outlines the measurements conducted at each study site. The points were five metres apart along transects with randomly determined starting points. Transects were used so that the points could be easily found on each measurement date. There were eight or nine points per plot depending on the transect layout. Owing to the unbalanced nature of the final sampling design, the data were analysed assuming a completely randomised design rather than a block design, with each sampling point treated as an independent replicate.

By analysing the data assuming a completely randomised design, the analysis was simpler than it would have been for an unbalanced randomised block design. However, the statistical power of the analysis is likely to have been less since the sampling design no longer controlled for natural variability in site characteristics such as soil type, slope and vegetation type between the blocks. An advantage of a block design over a completely randomised design is that natural variability between points within the same block is likely to be less than natural variability across all blocks (Moore and McCabe 1999; Ott and Longnecker 2001). This means there is a greater chance of detecting a treatment effect (i.e. a difference between the unburnt, low and high severity treatments) within a block design. Fortunately in this study, natural variability between the blocks is likely to have been minimal as the blocks within each site were chosen to have similar characteristics (see site descriptions – Section 3.7).

Table 7: Final sampling design at each study site. The numbers of sampled points per treatment plot are shown in brackets after each treatment.

	Site 1 (Upper Yarra)	Site 2 (Big Ben)	Site 3 (Mt Cole)
Block 1	Unburnt (9) Low severity 1 (8) Low severity 2 (6) High severity (9)	Unburnt (8) Low severity 1 (8) Low severity 2 (8)	Unburnt (8) Low severity (8) Low severity (8)
Block 2	Unburnt (9) Low severity (9)	Unburnt (8) Low severity 1 (8) Low severity 2 (8)	Unburnt (8) Low severity (8) Low severity (8)
Block 3	Unburnt (9) Low severity (9)[A]	Unburnt (8) Low severity 1 (8) Low severity 2 (8)	Unburnt (8) Low severity 1 (8) Low severity 2 (8)
Block 4	High severity 1 (9)[A] High severity 2 (9)[A]	High severity (8)[A]	

[A] Plots established after the burn – for points within these plots there were no pre-burn measurements or temperature measurements.

(a) Layout of points for all plots at Big Ben and Mt Cole.

(b) Layout of points for all plots except "block 1 high severity" at Upper Yarra.

(c) Layout of points for the "block 1 high severity" plots at Upper Yarra.

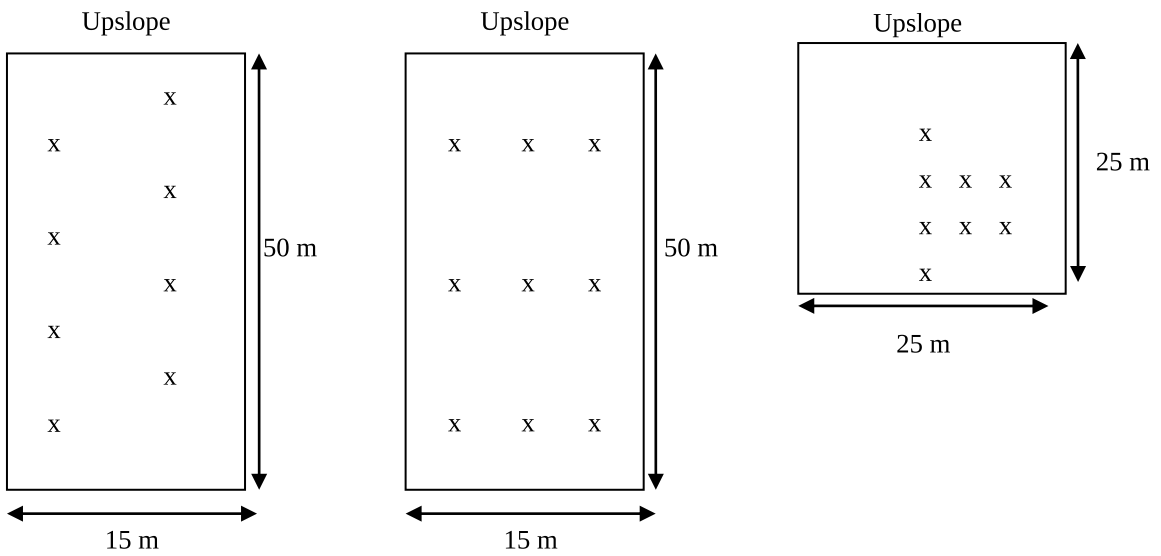


Figure 13: Layout of points within plots at Upper Yarra, Big Ben and Mt Cole. Direction of transects varied between sites (running across slope or downslope). The starting points for the transects were randomly determined. The layout of points at Upper Yarra "block 1 high severity" differed from the other plots because these points were originally established as part of a different study. Some plots at Upper Yarra in the low severity plots had fewer than nine points because large sections of the plot were unburnt and thus that area of the plot was deemed unburnt rather than low severity.

3.6.3 **Measurements outside the treatment plots**

In addition to the treatment plot measurements, rainfall simulations and hillslope runoff samplers were used to measure hydrological processes at Upper Yarra (Table 8). These measurements were done adjacent to the treatment plots in areas with the same vegetation, soil, aspect, and fire severity. Since these measurements were more resource intensive, they could only be performed at a single study site.

Table 8: Summary of measurements conducted at each site and the chapters where the results are reported.

Measurements	Timing of measurement	Upper Yarra	Big Ben	Mt Cole
In treatment plots:				
Soil temperatures – Chapter 4 (heat-sensitive liquids and thermocouples)	• during the burn	√	√	√
Point-scale soil water repellency – Chapter 4 (critical surface tension test)[A]	• immediately and 6 months post-burn	√	√	√
	• 12 and 18 months post-burn	√	×	×
Point-scale ponded infiltration – Chapter 5 (mini-disk ponded infiltrometer)[A]	• immediately and 6-months post-burn	√	√	√
	• 12 and 18 months post-burn	√	×	×
Point-scale tension infiltration – Chapter 5 (mini-disk tension infiltrometer)[A]	• immediately post-burn	×	×	√
	• 6 months post-burn	√	√	√
	• 12 and 18 months post-burn	√	×	×
Point-scale surface cover – Chapter 3 (visual estimates from photos)[A]	• Immediately and 6 months post-burn	√	√	√
	• 12 and 18 months post-burn	√	×	×
Outside treatment plots:				
Plot-scale runoff and erosion – Chapter 6 (rainfall simulations)[B]	• immediately and 12 months post burn	√	×	×
Hillslope runoff and erosion – Chapter 7 (hillslope runoff samplers)[B]	• following rainfall events from Aug-09 to Dec-10	√	×	×
Gravimetric soil moisture content – Chapter 3	• routinely (e.g. monthly)[A]	√	×	×
	• at the same time as other plot measurements	√	√	√
Rainfall, temperature, relative humidity and solar insolation using an automatic weather station – Chapter 7[B]	• three minute intervals from May-09 to Dec-10	√	×	×

[A] Owing to resource constraints these measurements were only done immediately post-burn and six-months post-burn at Big Ben and Mt Cole; [B] Owing to resource constraints these measurements could only be done at one study site.

3.7 Site descriptions

3.7.1 Location and geography

The study sites were located in Victoria, which is in the south-eastern corner of mainland Australia. There are seven distinct geomorphic zones in Victoria: Eastern Uplands, Western Uplands, Southern Uplands, Northern Riverine Plains, North Western Dunefields and Plains, Western Plains and Eastern Plains (Department of Primary Industries 2012). The Eastern and Western Uplands separate the streams and rivers draining to the Murray-Darling Basin from those flowing south, directly to the sea (Jenkin 1999; Joyce *et al.* 2003). The study sites were located in these uplands (Figure 11) – Mt Cole in the western uplands, and the Upper Yarra and Big Ben in the eastern uplands.

Most plots at Upper Yarra were within the McMahons Creek catchment, with the exception of the plots in Block 4, which were on the other side of the catchment divide in the Smoko Creek catchment (Figure 14). These creeks are tributaries to the Yarra River. The site was close to one of the major water supply reservoirs for Melbourne – the Upper Yarra reservoir. The plots were located within 100 m of the hillslope divide, had north to north-westerly aspects and slopes of 22^o to 26^o.

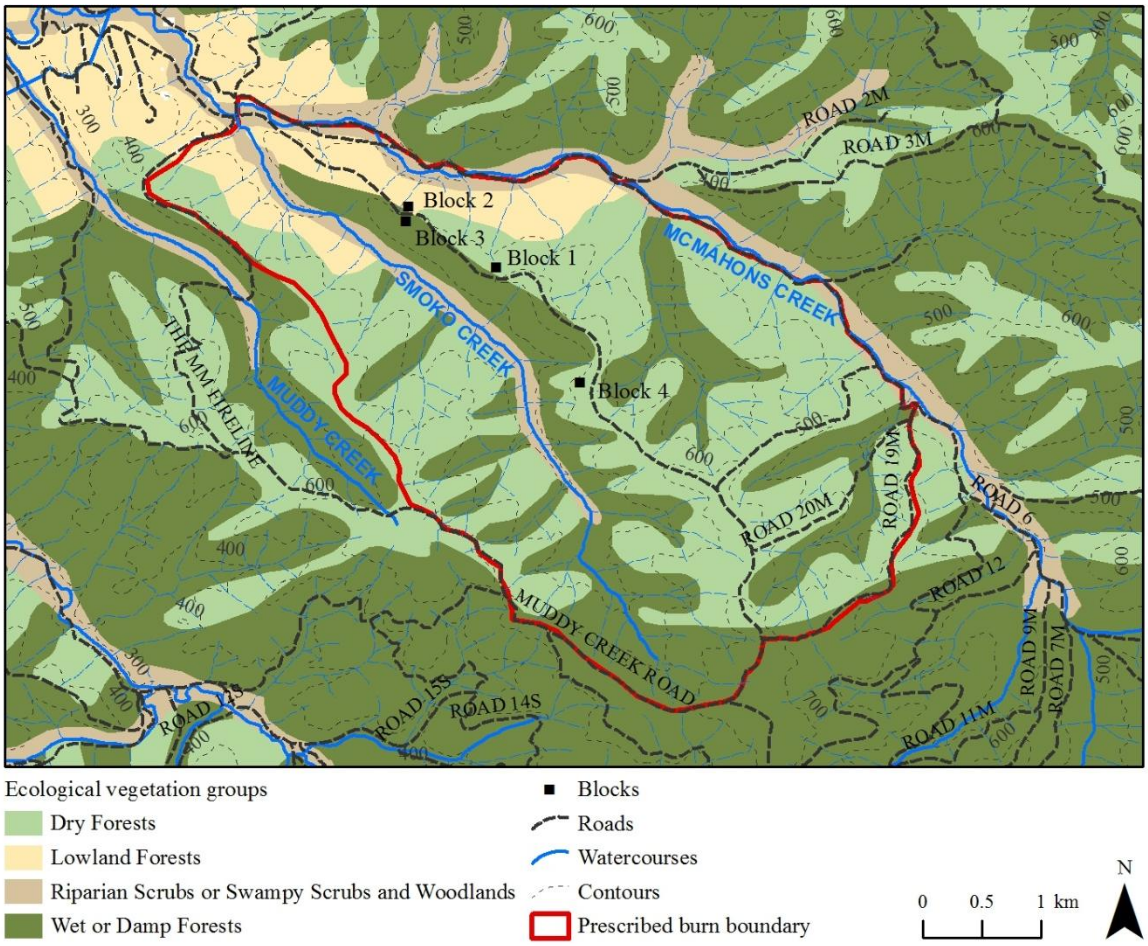


Figure 14: Location of blocks 1-4 at Upper Yarra. Block 1 contained high severity, low severity and unburnt plots; block 2 and 3 contained low severity and unburnt plots; block 4 contained high severity plots.

The Big Ben plots were located at the base of Mt Big Ben in catchments that are tributaries of the Kiewa River (via Kinchington Creek and Yackandandah Creek) (Figure 15). The plots had west to south-westerly aspects and slopes of 15° to 20°.

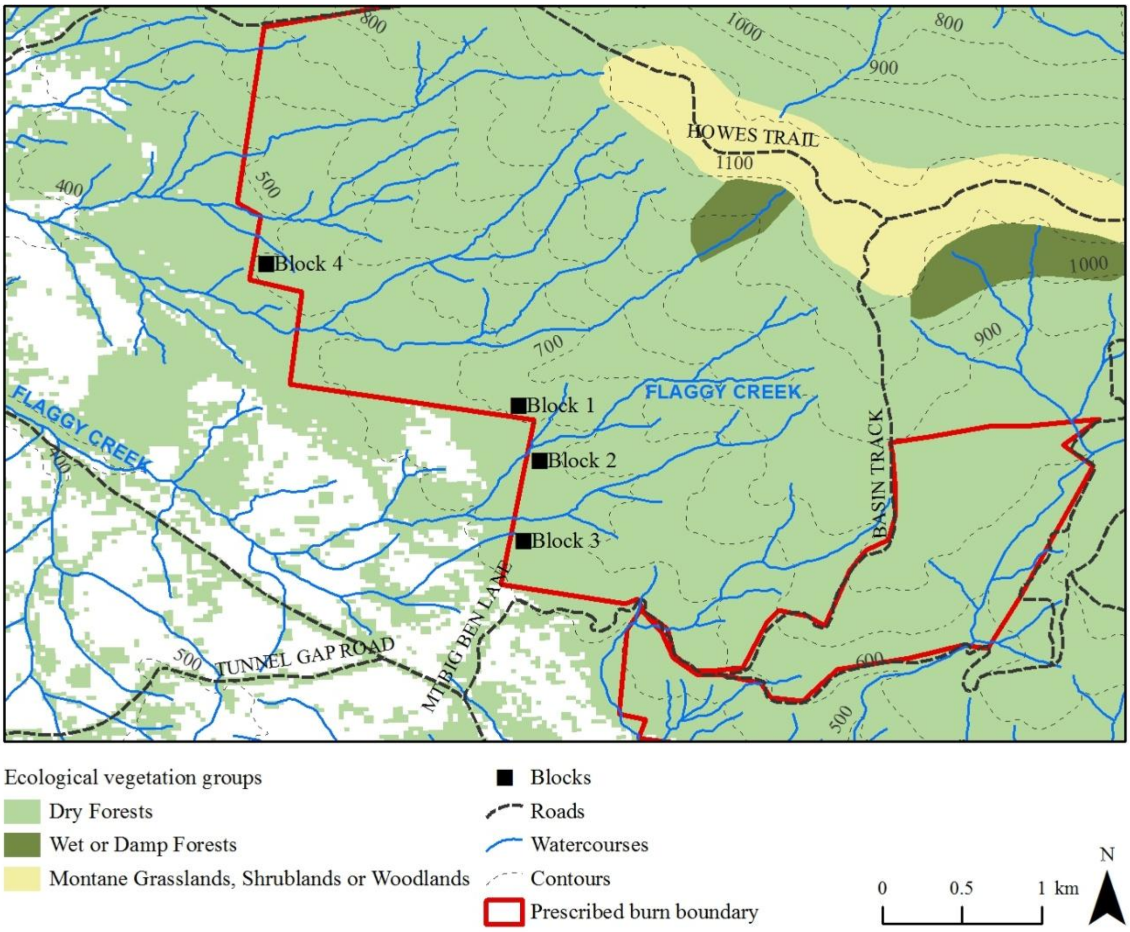


Figure 15: Location of blocks 1-4 at the Big Ben site. Blocks 1, 2 and 3 contained low severity and unburnt plots; Block 4 contained a high severity plot.

The Mt Cole plots were located in the Fiery Creek catchment, which supplies water for the local towns of Raglan and Beaufort (Figure 16). Water quality impacts resulting from burning are a concern for the local water authority (Central Highlands Water) and consequently the prescribed burn was cancelled before commencement in 2009. In 2010 the original burn boundary was modified and the site was burnt. All plots had a north-easterly aspect and slopes of 20° to 25°.

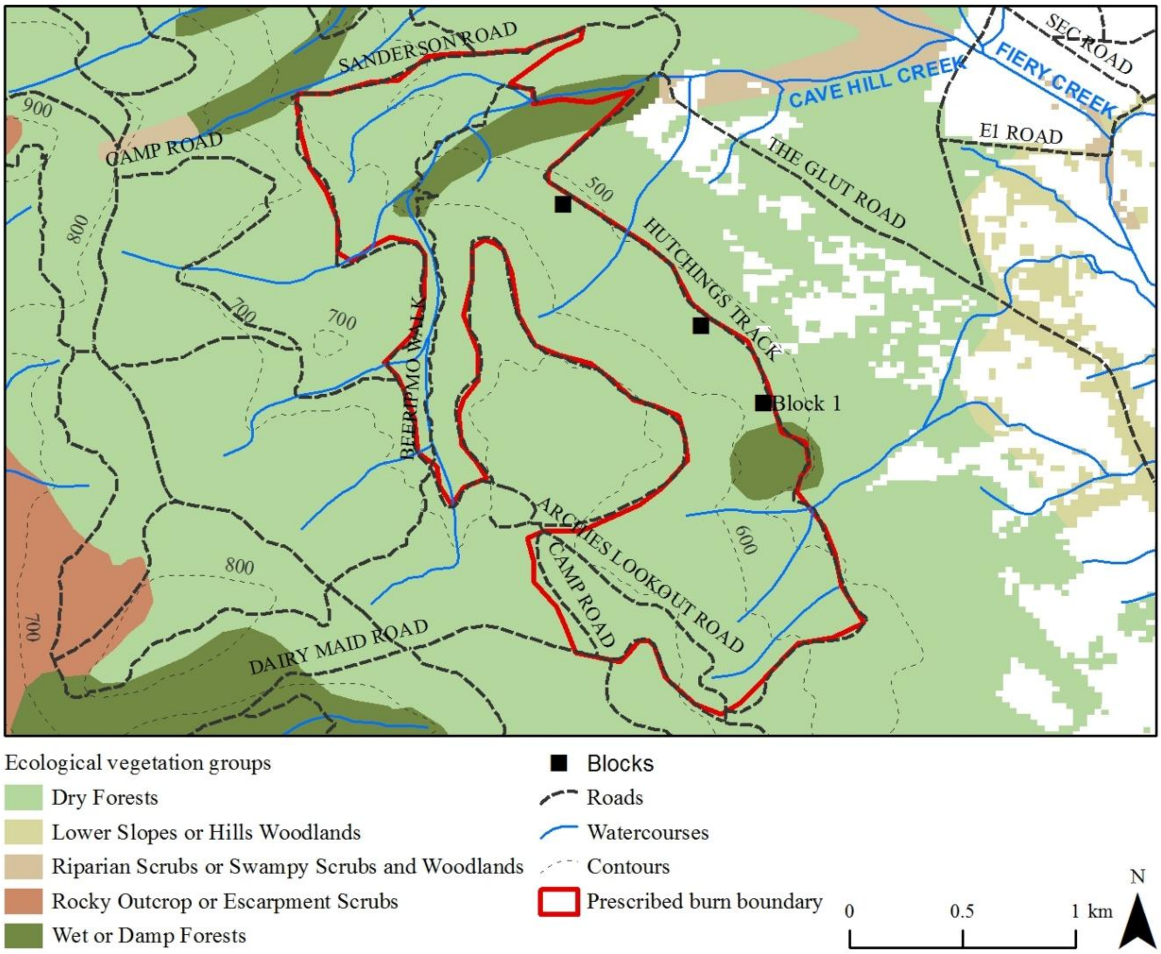


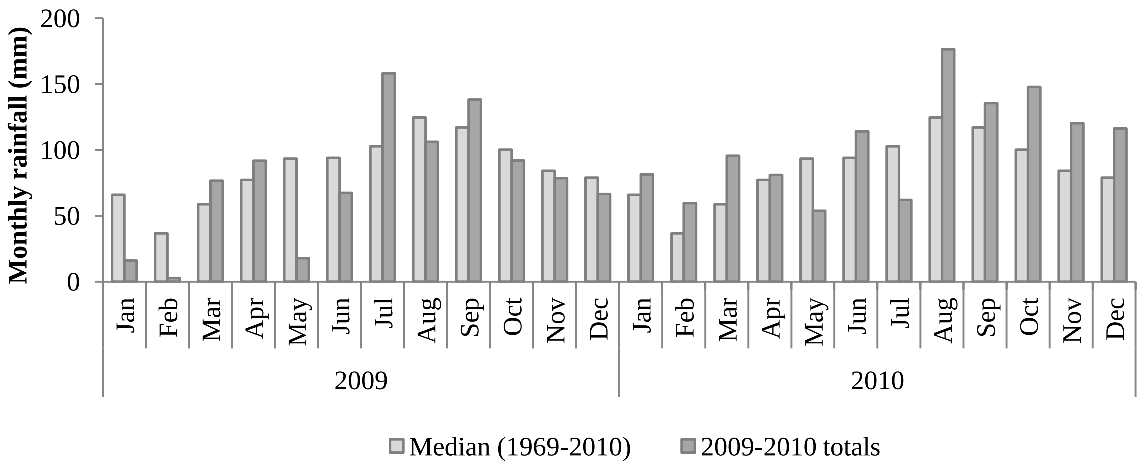
Figure 16: Location of blocks 1-3 at the Mt Cole site. Block 1 contains a low severity plot; Blocks 2 and 3 contain low severity and unburnt plots.

3.7.2 Climate averages and rainfall during the study period

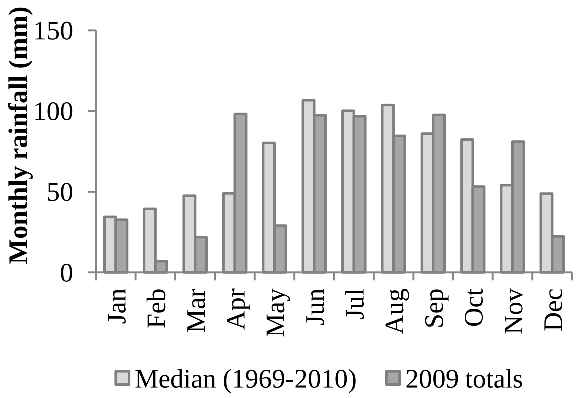
Most of Victoria is in a temperate climate zone, based on the Köppen classification, with no distinct dry season and mild to warm summers (depending on elevation) (Bureau of Meteorology 2005). The average minimum annual temperature is 9.5 °C and the maximum is 19.7 °C (based on measurements at Melbourne Airport from 1970 to 2010) (Bureau of Meteorology 2010b). The mean maximum temperature in the middle of summer (January) is 26.3 ^{o}C while in the middle of winter (July) it is 13 ^{o}C. Climatic variability in Victoria is related to changes in surface water temperatures in the Pacific Ocean and atmospheric circulation patterns (Walker circulation) in the Pacific region (Bureau of Meteorology 2005). Drier conditions occur when warmer surface water temperatures in the central to eastern Pacific Ocean cause a weakening of typical atmospheric circulation patterns (El Niño), which usually provide moisture for rainfall over Australia.

This study commenced towards the end of a long El Niño phase; annual rainfall in Victoria was below average for 13 years from 1997 to 2009 (Bureau of Meteorology 2010a). In the first part of 2009 there was below average rainfall at Upper Yarra in January, February, May and June (Figure 17a) and at Big Ben in February, March and May (Figure 17b). In contrast, 2010 was Victoria's fifth wettest year on record, with most of the rainfall recorded in the second half of the year (Bureau of Meteorology 2011). Monthly rainfall totals were above average in 2010 at Upper Yarra and Mt Cole from August to December (Figure 17).

(a) **Upper Yarra (Reefton weather station)**



(b) Big Ben (Yackandandah weather station)



(c) Mt Cole (Beaufort weather station)

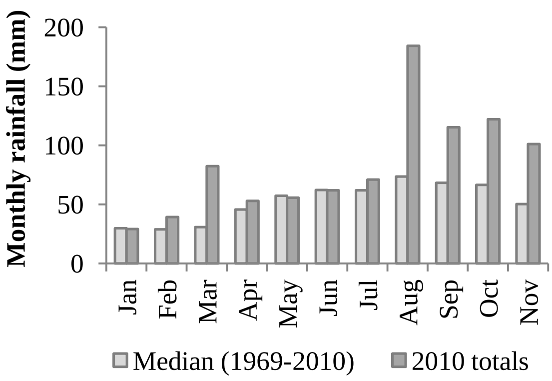


Figure 17: Monthly rainfall recorded at weather stations near each of the study sites. Totals during the study period are compared to the long-term medians (Bureau of Meteorology website: www.bom.gov.au).

3.7.3 **Vegetation**

The vegetation within all plots was broadly classified as dry forest (referred to throughout this thesis as ‘dry eucalypt forest’). Victoria’s vegetation is classified into about 300 Ecological Vegetation Classes (EVCs), a group of 11 similar classes in that system form the dry eucalypt forest group (Department of Sustainability and Environment 2011c). Dry eucalypt forest can be distinguished from other forest types on the basis of vegetation structure, species composition and regenerative mechanisms following fire. Specht (1970) describes dry eucalypt forest (or open forest) as having 30-70% projected foliage cover and trees that are 10-30 m tall. The species within dry eucalypt forests use several different mechanisms to regenerate following fire (Gill 1994). The eucalypt trees generally resprout from dormant epicormic buds beneath the bark on the trunk and branches. This contrasts with the eucalypts in wet eucalypt forests that are killed by fire and regenerate from seedlings. Some understorey species regenerate from dormant seeds stored in the soil while others release seed from woody capsules.

Key environmental factors influencing the distribution and form of dry eucalypt forest are rainfall, altitude, aspect and soil phosphorus (Gill 1994). Dry eucalypt forests occur in well-drained soils where the mean annual rainfall is more than 600 mm. They occur at elevations < 750 m on northerly aspects (i.e. in an arc from approximately 325^o to 45^o). The form of dry eucalypt forests varies from woodland-like (with shallow soils) on the most northerly aspects to taller forests (with deeper soils) on the least northerly aspects (Gill 1994). The study sites incorporate several varieties of dry eucalypt forest (Table 9) – heathy dry forest, shrubby foothill forest, grassy dry forest and herb-rich foothill forest (Figure 14, Figure 15 and Figure 16).

Table 9: Vegetation at each study site

Study site	Block	EVC group	EVC	Tree species	Approx. tree height (m)
Upper Yarra	1	Dry forest	Heathy dry forest and Shrubby foothill forest	*Eucalyptus dives*, *E. radiata*, *E. sieberi*, *E. cypellocarpa*.	7
	2 & 3	Dry forest	Shrubby foothill forest	*E. radiata*, *E. cypellocarpa.*	20
	4	Dry forest	Shrubby foothill forest	*E. sieberi*	20
Big Ben	1	Dry forest	Grassy dry forest	*E. goniocalyx*, *E. macrorhyncha*	12
	2	Dry forest	Herb-rich foothill forest	*E. obliqua*, *E. robertsonii and E. dives*	16
	3	Dry forest	Herb-rich foothill forest	*E. obliqua*, *E. robertsonii and E. dives*	18
	4	Dry forest	Herb-rich foothill forest	*E. obliqua*, *E. robertsonii and E. dives*	18
Mt Cole	1	Dry forest	Grassy dry forest	*E.viminalis*, *E. radiata*	24
	2	Dry forest	Herb-rich foothill forest	*E. viminalis*, *E.radiata*, *E. obliqua*	22
	3	Dry forest	Herb-rich foothill forest	*E. bicostata*, *E. radiata*	32

3.7.4 Geology and soils

Geology and soils are different at each site (Table 10). Soil textures were derived from bulk samples collected in each location and analysed in the laboratory using the pipette method for the finer fraction and sieving for the coarser fraction (Bowman and Hutka 2002). Organic matter content was determined using a loss on ignition method (samples heated in a muffle furnace at 550 ^{o}C for 3 hours). At the Upper Yarra the bedrock is sedimentary (folded siltstones, mudstones, shales and sandstones) and the soil texture is silty clay loam for all the treatment plots. At Big Ben the bedrock is metamorphic (schist and gneiss) and the soil is fine-textured and variable between the treatment plots (clay, clay loam and silty clay loam). The bedrock at Mt Cole is igneous (granitic) and the soil is coarser textured (sandy loams and loams). Bulk densities are slightly lower at Upper Yarra compared with Big Ben and Mt Cole. Organic matter content ranges from 6% to 17% across the three sites.

Table 10: Selected soil properties for surface soils (0-50 mm) at each study site.

Site	Block	Bulk density (g cm^{-3})	Organic matter (%)	Percent of each particle size for soil fine soil fraction i.e. gravel (> 2 mm) removed[A]				Soil texture (White, 1997)	Percent gravel (> 2mm)
				Clay <2 µm	Silt 2-20 µm	Fine sand >20-200 µm	Coarse sand 200-2000 µm		
Upper Yarra	1	0.8	10	40	34	25	2	Silty clay loam	17
	2	0.8	14	32	47	19	1	Silty clay loam	18
	3	0.8	9	28	51	20	1	Silty clay loam	15
	4	0.8	9	33	41	6	20	Silty clay loam	46
Big Ben	1	1.1	11	29	53	16	2	Silty clay loam	6
	2	1.0	9	34	23	22	21	Clay loam	5
	3	1.0	17	37	18	16	29	Clay	9
	4	1.0	7	33	28	17	22	Silty clay loam	14
Mt Cole	1	0.9	6	16	9	28	47	Sandy loam	21
	2	1.1	11	18	14	22	47	Loam	41
	3	1.1	6	11	10	11	68	Sandy loam	22

[A] Values do not add up to exactly 100% due to rounding errors.

3.7.5 Landscape-scale variability in soil hydrologic properties

Nyman *et al.* (2011) propose that the Victorian forested landscape may be grouped into three broad categories on the basis of soil hydrologic properties: dry forest, damp forest and wet forest. These groups accord with the groups of Ecological Vegetation Classes described earlier (Section 3.7.3). Dry forests are characterised by shallower soils, lower infiltration rates and a greater propensity for post-fire erosion (Table 11). Conversely, wet forests are characterised by deeper soils, higher infiltration rates and less propensity for post-fire erosion. There has been little hydrologic research to characterise the post-fire hydrologic properties of dry forests (some exceptions are Doerr *et al.* 2004; Doerr *et al.* 2006; Nyman *et al.* 2010b; Nyman *et al.* 2011; Prosser and Williams 1998), which is one reason why they are the focus of this thesis. Additionally, as mentioned above, the hydrologic properties of dry forests are thought to make them more susceptible to post-fire runoff and erosion than the wet and damp forests (Nyman *et al.* 2011).

Table 11: Hydrologic properties of dry and wet forest categories in unburnt soils. Data summarised from Nyman *et al.* (2011) unless otherwise stated.

Forest type	Ground cover (%)	Litter depth (mm)	Soil depth (m)	Field saturated infiltration (mm h^{-1})	Susceptibility to post-fire erosion
Dry forest	50-80	10-30	0.2-1	43	High
Wet forest	100	100	1-3	1001 (Sheridan *et al.* 2007)	Low

3.7.6 Fire history and other disturbances

Another key reason for targeting dry eucalypt forests in this study is that they are frequently burnt by prescribed fire. In Victoria more dry eucalypt forest was prescribed burnt than any other Ecological Vegetation Group between 1988 and 2008 (Figure 18). Cheal (2010) suggests that from an ecological perspective the tolerable fire interval for such forests is 10-100 years (for foothill forest). Records show that the Upper Yarra site was last burnt by wildfire in 1939 and the Big Ben and Mt Cole sites were both last burnt by prescribed burns in 2002 and 1994, respectively (Department of Sustainability and Environment 2011a).

The relatively recent past fires at Big Ben and Mt Cole could mean that fuels loads had not fully recovered at the time of the prescribed burns for the present study. Chatto (1996) reported that following fire in a dry eucalypt forest with a mainly grassy understorey in north-eastern Victoria, surface fine fuels loads reached an equilibrium level within three years and elevated fine fuels loads within nine years. Fogarty (1993) reported that following fire in a dry eucalypt forest with a wiregrass understorey in eastern Victoria, total fine fuel loads re-accumulated within 15 years with half of that re-accumulating within the first four years. For this thesis, surface fuel loads were measured prior to burning by collecting, oven-drying (at 100 ^{o}C for seven days) and weighing all the forest floor litter in 0.1 m^2 quadrats (n = 54, 72 and 21 at Upper Yarra, Big Ben and Mt Cole, respectively). Based on those measurements, mean surface fuel loads were 6.8 t ha^{-1}, 9.8 t ha^{-1} and 9.3 t ha^{-1} at Upper Yarra, Big Ben and Mt Cole, respectively.

In terms of other disturbances, it is likely that all the study sites were logged at some point in their history. Since the arrival of Europeans in Victoria there has been widespread land clearing to make way for settlements, agriculture and mining, with many forested areas logged for timber. Government records (Department of Sustainability and Environment 2011b) are incomplete for the study sites but show a history of timber harvesting in the early 1960s at Upper Yarra, affecting Blocks 3 and 4. There are no records available for the remainder of Upper Yarra, Big Ben or Mt Cole.

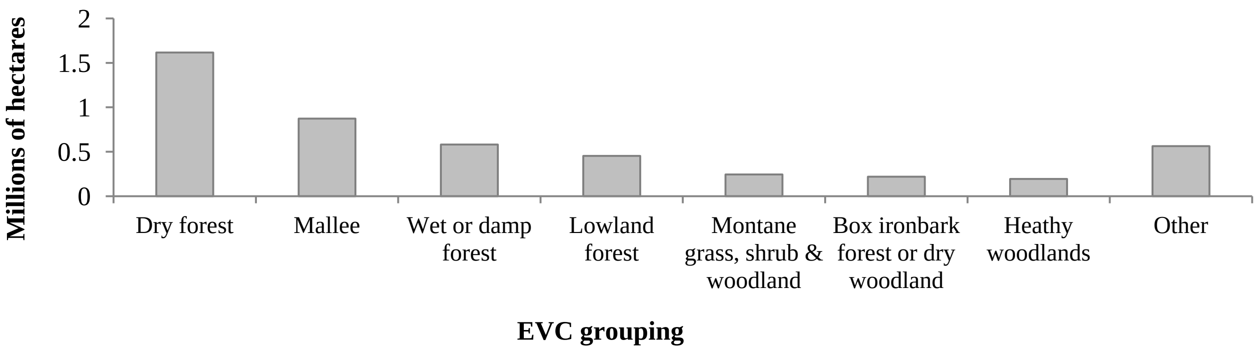


Figure 18: Area of each vegetation burnt by prescribed fire at least once in the last 20 years (1988-2008). Derived from spatial data provided by the Department of Sustainability and Environment.

3.7.7 **Burn treatments**

The characteristics of the burnt plots at each study site are described in Table 12 and illustrated in Figure 19. The low severity plots at the Upper Yarra and Big Ben had numerous unburnt patches within them (28-35% of the sample points were unburnt) whereas at Mt Cole there were no unburnt sample points.

Fuel consumption was determined in the low severity plots by collecting pre-burn samples of surface litter and post-burn samples of ash in 0.1 m^2 quadrats near each of the sample points (n = 54, 72 and 21 at Upper Yarra, Big Ben and Mt Cole, respectively). The pre-burn samples were oven-dried (at 100 ^{o}C for seven days) and weighed (as described earlier to determine pre-burn fuel loads). The post-burn samples were weighed in the field using a spring balance (moisture contents were assumed to be very low as sampling was done within hours of burning). For each sample point, post-burn ash weights were subtracted from pre-burn fuel weights to determine the percentage of fuel consumed. Fuel consumption was similar for all study sites (with mean values ranging from 45% to 46%) but the mass of surface fuel consumed at Mt Cole was slightly higher (5.1 t ha^{-1}, 4.2 t ha^{-1} and 4.6 t ha^{-1} at Mt Cole, Upper Yarra and Big Ben, respectively). There were no measurements for the high severity plots because these plots were established post-burn and hence there were no pre-burn fuel samples.

The fire severity scale in Figure 20 puts the fire severities observed at the study sites into a broader context. It shows that while the fire severities observed at the study sites may be representative of those occurring in prescribed burns, they do not cover the full spectrum of fire severities that may result from wildfires.

Table 12: Characteristics of burnt areas at the study sites

Site	Fire severity	Visual characteristics	Scorch height (m)	Surface fuel consumed[A]		Unburnt sample points (%)
				Load (t ha^{-1})	Percent	
Upper Yarra	Low	Surface fuels patchily burnt; understorey unburnt or scorched; canopy unburnt	0.1–1.6	4.2	46	28
	High	Surface fuels completely burnt; understorey completely burnt; Canopy scorched or burnt	30	-	-	0
Big Ben	Low	Surface fuels patchily burnt; understorey unburnt; canopy unburnt	0.1–1	4.6	46	35
	High	Surface fuels completely burnt; understorey scorched or burnt; canopy partially scorched	15	-	-	0
Mt Cole	Low	Surface fuels completely burnt; understorey scorched or unburnt; canopy unburnt	0.1– 5	5.1	45	0

[A] Calculated from the difference in weight of pre- and post-burn surface fuel samples. Surface fuel is the fuel on the forest floor.

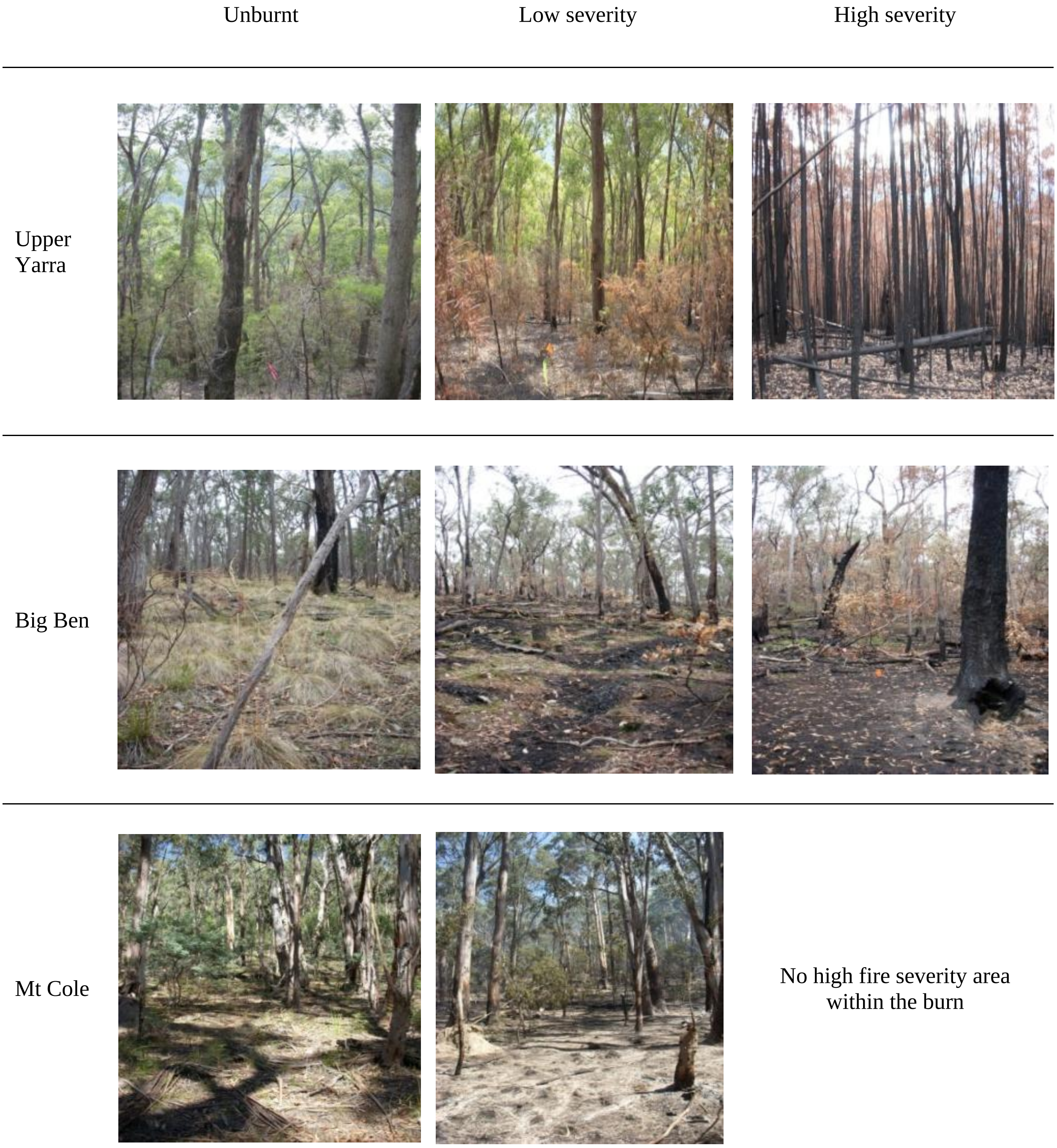


Figure 19: Photographs to illustrate the fire severities at each of the study sites

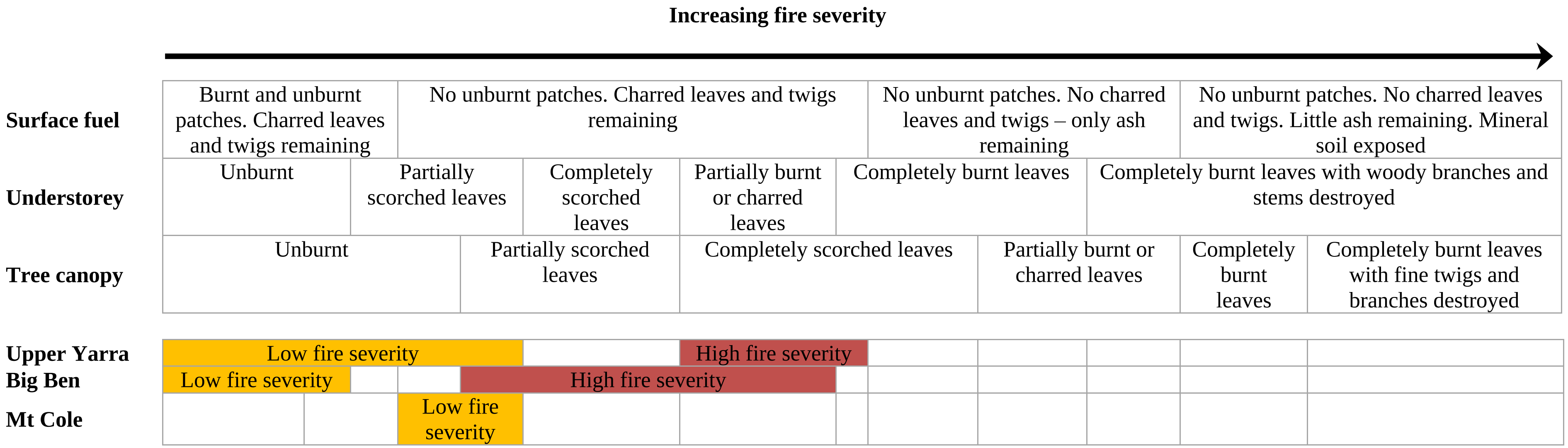


Figure 20: A qualitative scale-bar to illustrate where the fire severities in this study fit more broadly within the full spectrum of fire severities that may result from forest fire.

4. Effects of prescribed burning on point-scale soil water repellency

This chapter quantifies the effects of fire severity on soil water repellency at the point-scale using the critical surface tension test at the Upper Yarra, Big Ben and Mt Cole.[1]

4.1 Introduction

Soil water repellency (referred to as water repellency) is considered an important soil hydrologic property as it has been associated with low infiltration capacities and enhanced surface runoff and erosion (see reviews by DeBano 1981; DeBano 2000; Doerr *et al.* 2000; Letey 2001). Its presence is indicated by the contact angle of a water droplet resting on the soil surface being > 90^{o}, thus preventing the water from immediately soaking into the soil (Letey 2001). Soil water repellency is thought to be caused by organic material on the soil surface or in the soil profile (DeBano 1981; Doerr *et al.* 2000); some plants are more commonly associated with soil water repellency, such as evergreen trees (e.g. eucalypts and pines) with large amounts of resin, wax or aromatic oil (Doerr *et al.* 2000). Water repellency is most commonly found in coarse-textured soils, but is more intense in fine-textured soils (i.e. water is more strongly repelled for a longer duration in fine-textured soils) (Doerr *et al.* 2000). It may be eliminated above certain soil moisture thresholds (Doerr and Thomas 2000), resulting in seasonal fluctuations (Keizer *et al.* 2008; Leighton-Boyce *et al.* 2005; Sheridan *et al.* 2007).

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[1] Note: the soil temperature measurements (pyrometer and thermocouple) and water repellency measurements immediately post-burn from one high severity plot (Block 1) at Upper Yarra were collected by Petter Nyman.

Burning can strengthen, translocate 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). Laboratory studies report temperature thresholds for the intensification and destruction of water repellency (as summarised by DeBano 2000): (1) < 175 ^{o}C there is no change to water repellency; (2) 175-200 ^{o}C water repellency intensifies; and (3) 280-400 ^{o}C water repellency is destroyed. In soils with pre-existing water repellency, it may be destroyed in the surface soils and intensified below the surface (e.g. Doerr *et al.* 2006).

While these relationships between soil heating and water repellency are strong in the laboratory, few studies investigate the direct link between these two variables in the field where relationships may be different (exceptions include Stoof *et al.* 2011; Vadilonga *et al.* 2008). Vadilonga *et al.* (2008) reported a slight increase in water repellency for temperatures > 400 ^{o}C and a slight decrease for temperatures < 200 ^{o}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 temperatures during the burn (i.e. 60 ^{o}C). Better definition of the relationship between soil heating and water repellency in the field is an important step towards improving management of the effects of prescribed burning on surface runoff and erosion, since soil temperatures during a prescribed burn could be controlled to some extent (via ignition patterns and the choice of weather conditions and fuel moisture contents).

Fire severity – a measure of the loss of organic matter as a result of fire (Keeley 2009) – may be a useful indicator of soil heating and changes to soil water repellency. It is already used in some post-fire assessments (e.g. fire severity mapping is a central component of the Burned Area Emergency Rehabilitation (BAER) assessments in the USA; Parsons 2003). Yet, very few studies have measured all three factors (fire severity, soil heating and water repellency) in the same burn area (Vadilonga *et al.* 2008 is one exception), and as discussed in Chapter 2, relationships between fire severity and water repellency have been difficult to establish in past studies. Therefore, the purpose of this chapter is to quantify links between fire severity, soil heating and water repellency in dry eucalypt forests following prescribed burning. The following hypotheses are addressed:

- Prescribed burning changes soil water repellency (Hypothesis A in Chapter 3)
- Changes to soil water repellency following prescribed burning are related to the fire severity (Hypothesis A1 in Chapter 3)
- Soil water repellency recovers fully within 18-months of prescribed burning (Hypothesis A2 in Chapter 3).

There are two common methods for measuring soil water repellency – the critical surface tension (CST) test and the water drop penetration time (WDPT) test (as reviewed by Doerr *et al.* 2000; Letey 2001; Letey *et al.* 2000). The CST method measures the apparent surface tension of the soil (i.e. how strongly water is repelled). It involves reducing the surface tension of water by mixing water with ethanol to different concentrations. Droplets of the ethanol solutions are placed onto the soil and the highest surface tension at which the water droplet immediately soaks into the soil is the critical surface tension. In contrast, the WDPT test measures the stability of soil water repellency beneath a water droplet. It involves measuring the time required for a droplet of water on the soil to soak in. Both methods have their advantages and disadvantages (Table 13), but have been shown to provide comparable results (King 1981; Scott 2000). For this study, the CST method was used because it is more effective at distinguishing the strength of water repellency in soils that are strongly repellent (eucalypt forest soils are likely to be strongly repellent; Doerr *et al.* 2004) and it can be more rapidly implemented than the WDPT test.

Table 13: Advantages and disadvantages of common measurement techniques to assess soil water repellency (Doerr *et al.* 2000; King 1981; Letey 2001; Letey *et al.* 2000; Scott 2000).

Technique	Advantages	Disadvantages
Critical surface tension (CST)	Fast to perform regardless of the strength of water repellency. Provides a measure of initial strength of water repellency. Estimates the soil-water contact angle (i.e. the strength of water repellency). Provides a numeric classification of water repellency, which has more statistical utility than categorical data.	Requires more equipment – i.e. a range of aqueous ethanol solutions, which can be awkward to handle in the field.
Water drop penetration time (WDPT)	Simple to implement and rapidly determines the presence/absence of water repellency. Requires minimal equipment or preparation. Provides insight into the potential persistence of water repellency during a rainfall event.	Time consuming to determine the persistence of water repellency in highly repellent soils. Difficult to distinguish between degrees of water repellency in strongly repellent soils. Sensitive to water drop size.

4.2 Methods

The data reported in this chapter were collected from permanent points within the fire severity plots at each study site – Upper Yarra, Big Ben and Mt Cole (described in Chapter 3). Soil temperatures during the burn were measured at each point (excluding those points in the high fire severity plots established after the burn). Water repellency was measured at each point immediately post-burn in autumn and six-months post-burn in spring (Table 8 in Chapter 3). Additional water repellency measurements were carried out 12- and 18-months post-burn at Upper Yarra.

4.2.1 Soil temperature

Surface and sub-surface temperatures were measured using thermocouples and heat-sensitive liquids (pyrometers). The thermocouples provided the most accurate temperature measurements and also provided a time-series at one second intervals. Up to 20 thermocouples (3 mm diameter) were installed at each site at depths of 0 to 35 mm. The pyrometers were less accurate but provided better spatial coverage as they were installed in large numbers. Heat-sensitive liquids (Tempilaq brand), with melting points from 79 °C to 1038 °C, were painted onto ceramic tiles or aluminium flashing (Figure 21). Tiles were used for surface measurements and flashing for sub-surface measurements. Flashing is a more effective heat conductor (Tolhurst 1995) but it can melt under high temperatures at the soil surface. The tiles were wrapped in aluminium foil and the flashing was folded in half to prevent blackening of the marked surfaces during burning. Three pyrometers were installed at each sampling point; one on the mineral soil surface beneath the leaf litter and two buried approximately 20 mm and 50 mm below the soil surface. Care was taken to minimise soil disturbance during their installation. The thermocouples and pyrometers were installed 1-3 days prior to burning and removed 1-2 days post-burn.

(a) **(b)**

Figure 21: (a) Thermocouple installation and (b) pyrometer installation.

At Mt Cole, pyrometers were installed within 100 mm (horizontally) of each thermocouple so that comparisons could be made between the measurement devices. Those comparisons showed that the pyrometer and thermocouple temperatures were poorly correlated (r = 0.15) with the pyrometers frequently underestimating the maximum temperature relative to the thermocouple maxima (Figure

22a). However, when the duration of heating was taken into consideration for the thermocouple measurements, the strength of that correlation improved (Figure 22b and c). For example, when the pyrometer temperature was compared with the minimum thermocouple temperature during the hottest 10 minutes the correlation coefficient (r) was 0.35 (Figure 22c). It appears that the pyrometers required longer heating durations than the thermocouples to detect a temperature change, and therefore the temperatures measured by the pyrometers were not the absolute maximum temperatures, but rather the maximum temperatures exceeded for a period of 5-10 minutes (Figure 23). The remaining variation between the paired thermocouple-pyrometer measurements is likely to have been caused by many other factors including differences in fuel size and fuel arrangement immediately above the measurement device.

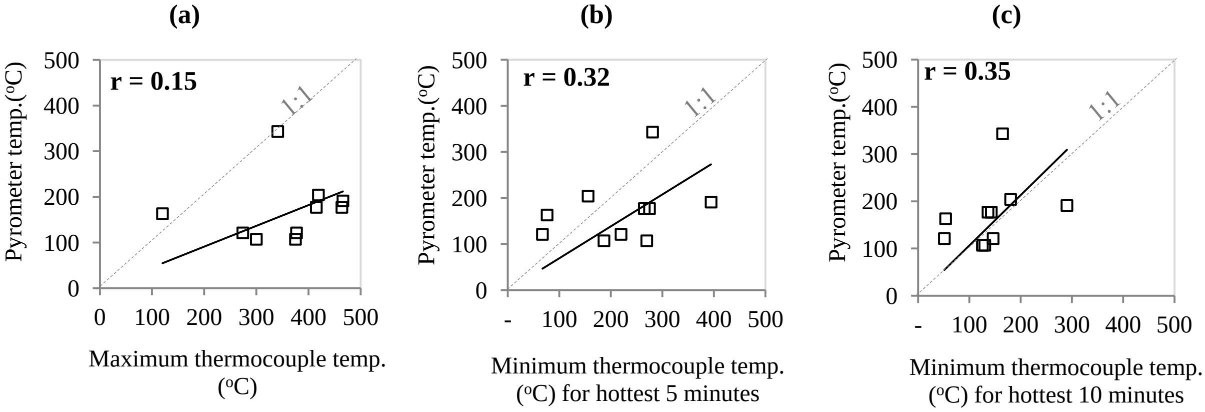


Figure 22: Pyrometer temperatures versus (a) maximum thermocouple temperatures, (b) minimum thermocouple temperatures for hottest five minutes and (c) minimum thermocouple temperature for hottest 10 minutes. Data are for paired pyrometers and thermocouples (spaced within 100 mm horizontally of each other) on the soil surface at Mt Cole.

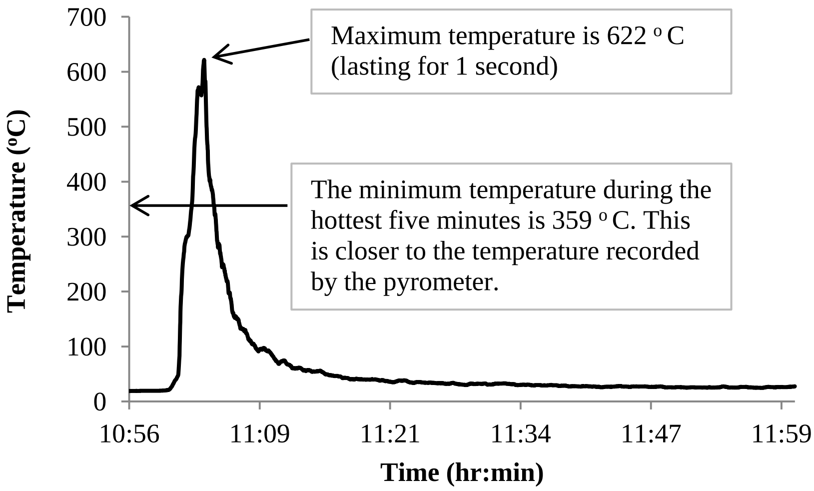


Figure 23: Time-series of temperatures measured by a thermocouple (UY1) at the soil surface.

4.2.2 Soil water repellency

Soil water repellency was measured within 1 m of each soil temperature sampling point at the following depths: 0 mm, 10 mm, 20 mm, 30 mm, 40 mm, 50 mm, 75 mm and 100 mm. Leaf litter and ash were removed from a flat section of the soil surface with a brush for the surface (0 mm) measurements. Nearby a small trench was dug to provide a flat surface at the required depths beneath the soil surface (Figure 24). Soil water repellency was measured at each depth using the critical surface tension (CST) method with 15 ethanol solutions increasing in concentration by 0.4 M (i.e. 0.4 mol L^{-1}), from 0 M (distilled water) to 5.6 M. Increasingly higher concentrations were dropped onto the soil from a height of approximately 2 cm until the droplets were absorbed into the soil within five seconds. The minimum ethanol concentration at which two or more droplets were absorbed was recorded. Since the measurements were done *in situ*, the soils were subject to the prevailing moisture conditions, which means that the measurements reflect both the impact of the burn and the moisture conditions.

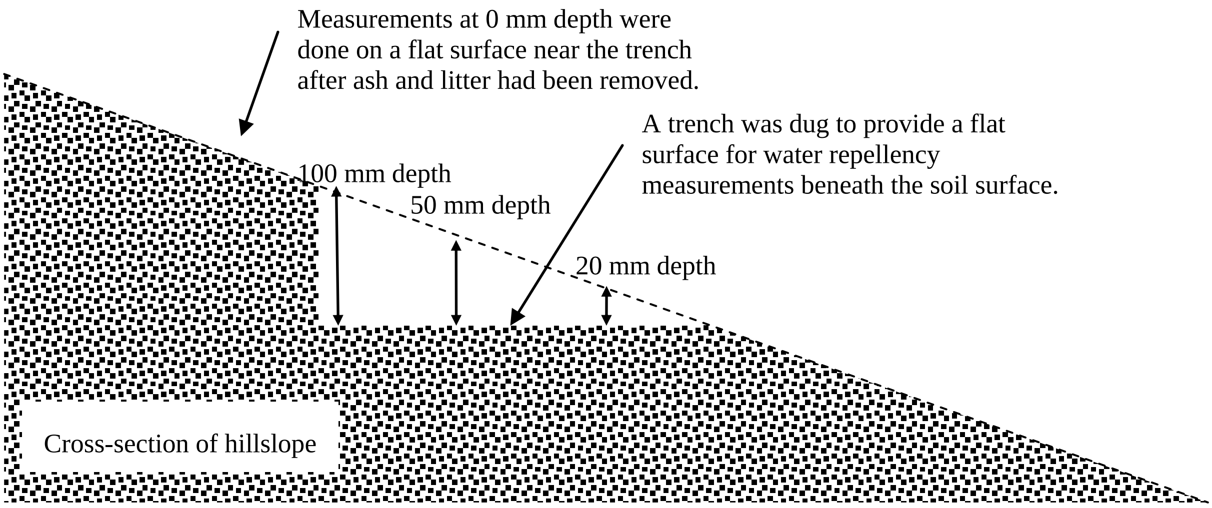


Figure 24: Diagram to illustrate the trenches used to measure soil water repellency on flat surfaces at a range of depths.

4.2.3 **Soil moisture content**

Soil moisture contents were measured gravimetrically within each treatment plot at the same time as the water repellency measurements and also at the same time as some of the runoff sampler measurements (see Chapter 7). Bulk samples were collected at two depth ranges (0-20 mm and 20-50 mm) from five locations within each plot. The samples were weighed in the laboratory (± 0.01 g), oven dried (100 ^{o}C for seven days) and then reweighed.

4.2.4 **Data analysis**

The data were analysed assuming a completely randomised design, rather than the randomised block design that was originally intended (as discussed in Chapter 3). Soil temperature (mean pyrometer temperature) and water repellency (median CST) were analysed using t-tests (for temperature) and Mann Whitney tests (for water repellency) to identify significant differences ($p < 0.05$) between the fire severities, study sites and soil depths. Mann Whitney tests were used for the water repellency data since they were strongly skewed; the temperature data were approximately normally distributed. The water repellency data were also analysed categorically by grouping the data into the classes outlined in Table 14. Statistical tests (chi-square tests of independence) were used to identify significant differences ($p < 0.05$) between fire severities, study sites and depths. The pyrometer temperatures were also grouped into classes (< 100 ^{o}C, 100-200 ^{o}C, 200-300 ^{o}C and > 300 ^{o}C) and chi-square tests were performed to identify significant differences ($p < 0.05$) in the strength of water repellency associated with each temperature class.

Table 14: Classification of soil water repellency based on the molarity of ethanol solutions and surface tension

Ethanol concentration (M)	**Surface tensions for 25 ^{o}C (mN m^{-1})**	**Soil water repellency class** (adapted from Woods *et al.* 2007)
0	72	Non-repellent
0.4 - 1.6	62.9 - 48.2	Slightly repellent
2 - 2.8	45.3 - 40.8	Moderately repellent
3.2 - 4.8	39.1- 34.1	Strongly repellent
5.2 - 5.6	33.1 - 32.3	Very strongly repellent

4.3 Results

4.3.1 Soil heating

Mean surface temperatures were significantly greater for the high severity (228 ^{o}C) than for the low severity points (123 ^{o}C) at Upper Yarra (Figure 25). There were no significant differences in surface temperatures between the low severity points at Upper Yarra (123 ^{o}C) and Big Ben (99 ^{o}C), while at Mt Cole the low severity points were significantly hotter (228 ^{o}C) and therefore more comparable to the high severity points at the Upper Yarra. Temperatures decreased with soil depth and rarely exceeded 100 ^{o}C below the soil surface (Figure 25 and Figure 26). While peak temperatures measured with the thermocouples reached 622 ^{o}C (Upper Yarra), 288 ^{o}C (Big Ben) and 466 ^{o}C (Mt Cole), the durations of these peak / high temperatures were short. For example, mean durations above 175 ^{o}C (associated with changes to water repellency in laboratory studies; DeBano, 2000) were 7.4 min, 1.2 min and 10.3 min at Upper Yarra, Big Ben and Mt Cole, respectively (Figure 26).

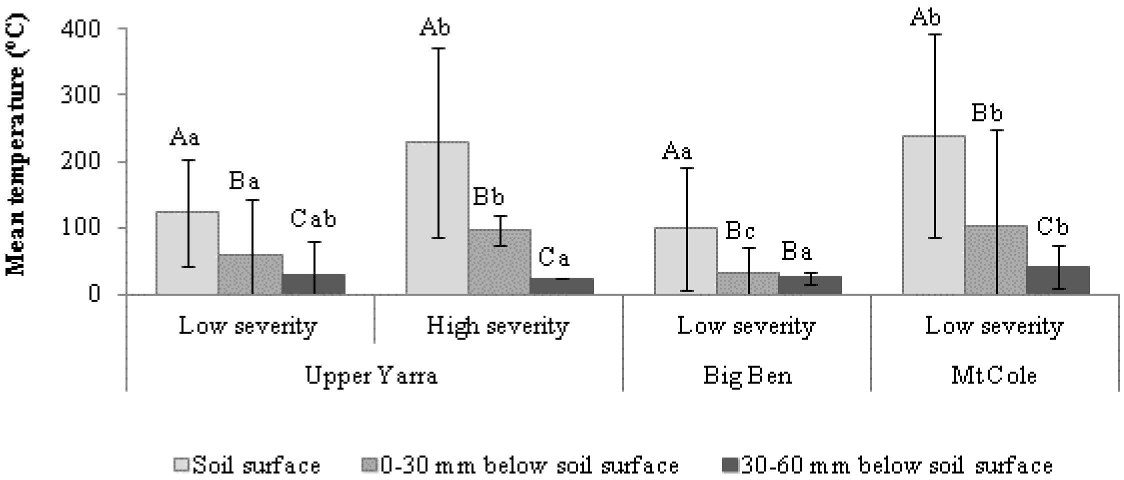


Figure 25: Mean pyrometer temperatures for various soil depth classes: 0 mm, 0-30 mm, 30-60 mm and > 60 mm at the Upper Yarra, Big Ben and Mt Cole. Error bars denote the standard deviations. Letters above each column denote the outcome of t-tests (the same letter means no significant difference; $p < 0.05$). Upper case letters are for t-tests comparing different soil depths within the same study site / fire severity. Lower case letters are for t-tests comparing study sites/fire severities at the same soil depth.

(a) Maximum temperature × depth **(b) Duration of heating above threshold temperatures**

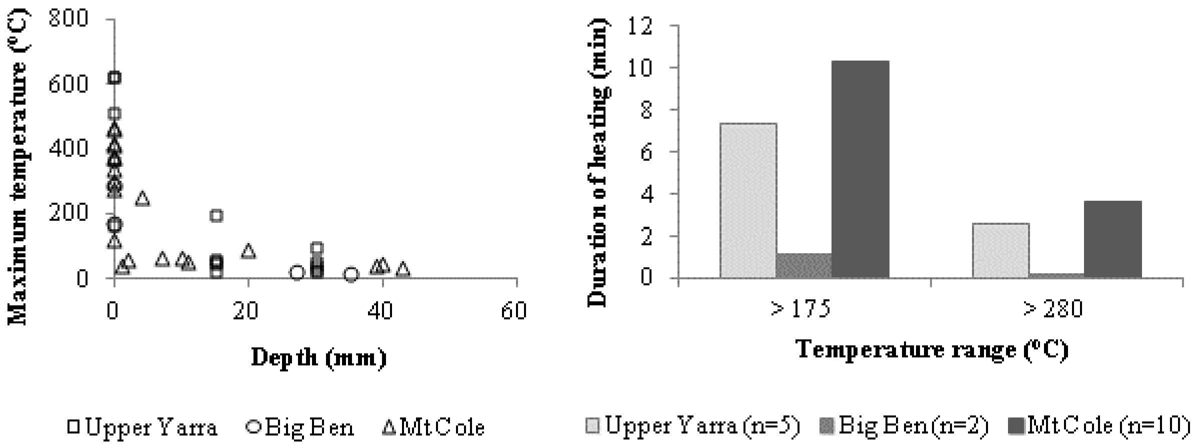


Figure 26: Summary of thermocouple measurements: (a) maximum temperature as a function of depth, and (b) duration of heating above threshold temperatures. The threshold temperatures (based on laboratory studies) are associated with the strengthening (> 175 °C) and destruction (280 °C) of soil water repellency (DeBano 2000).

4.3.2 Soil water repellency immediately post-burn

Water repellency was present in unburnt areas at all sites (Figure 27) (30-56% of points were at least slightly repellent at the surface). At Upper Yarra and Mt Cole, burning increased water repellency (respectively, 83-100% and 90% of points were at least slightly repellent). These increases in water repellency are statistically significant for the surface soils (chi-square tests; $p < 0.05$). At Mt Cole, burning appeared to increase water repellency beneath the soil surface (Figure 28). There were apparently no effects of burning on water repellency at Big Ben, or of fire severity on water repellency at the Upper Yarra. Water repellency generally decreased with depth, except at Big Ben where it was non-repellent at the soil surface.

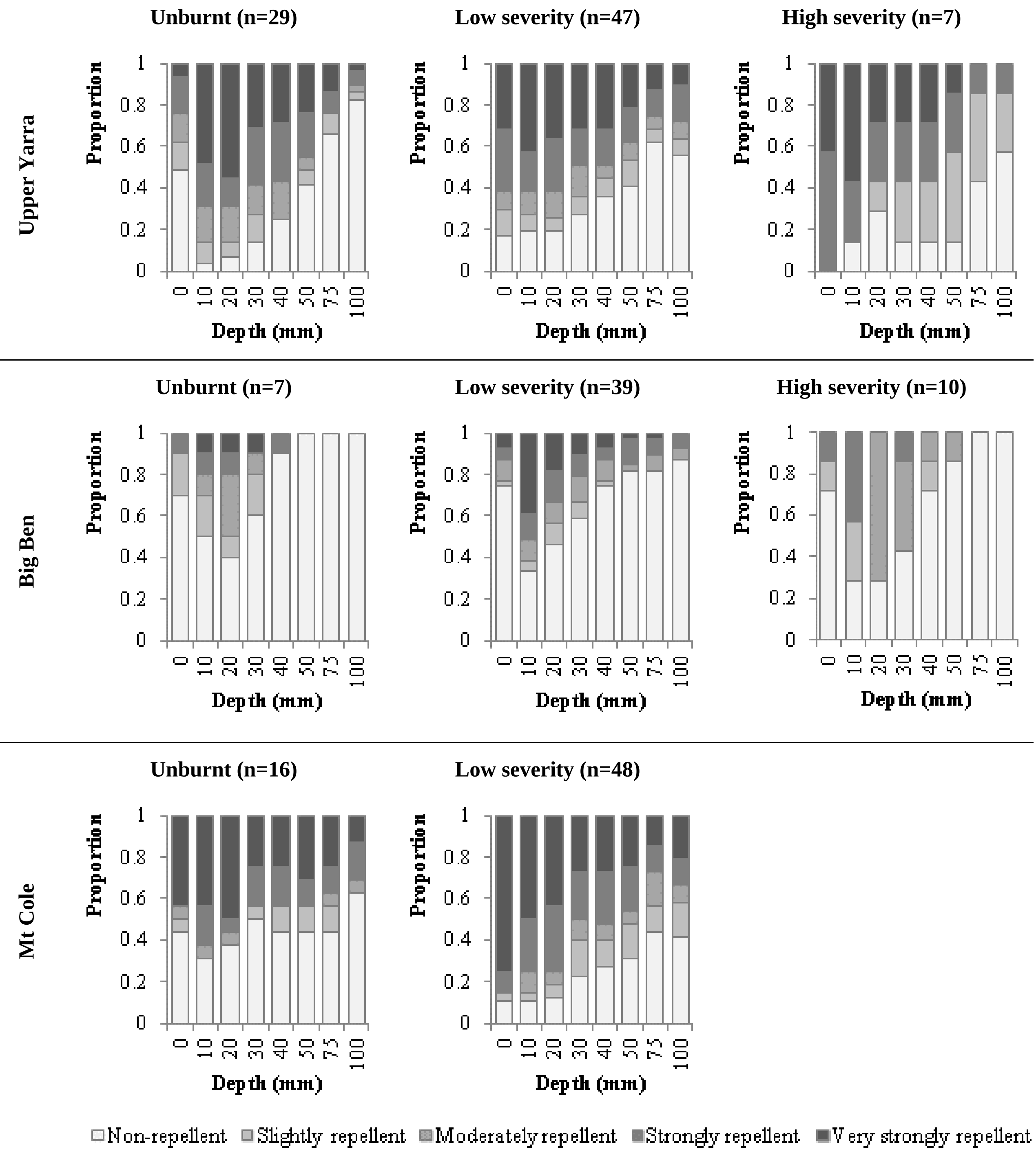
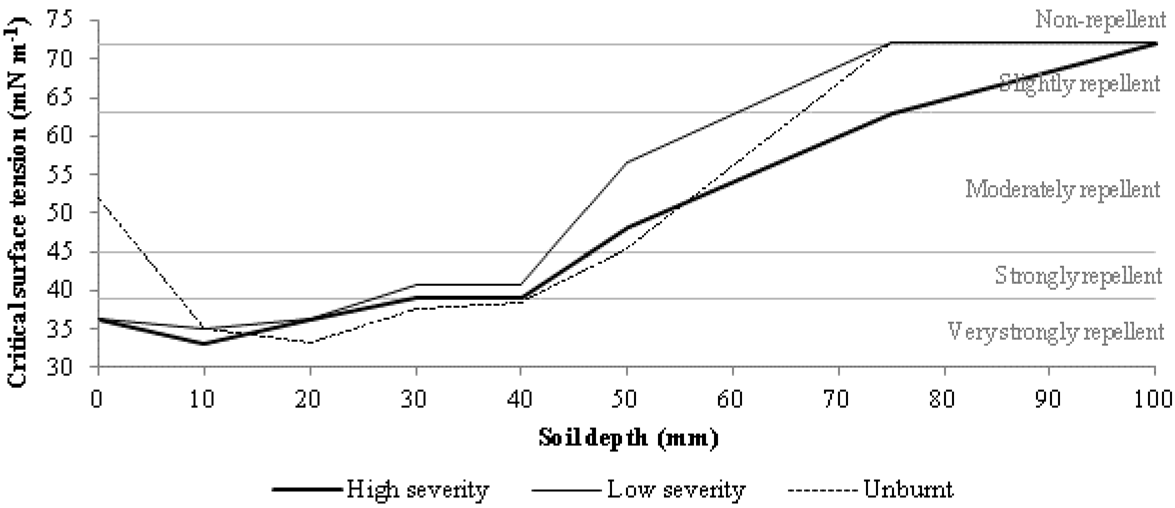
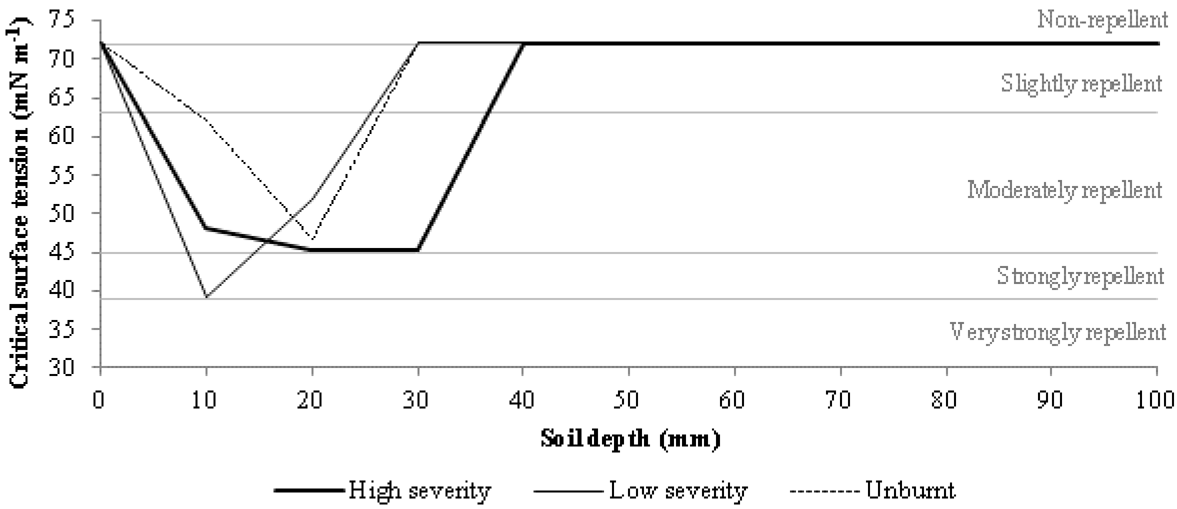


Figure 27: Soil water repellency less than 2 months after burning. Charts show the proportion of measurements in each water repellency class for different soil depths, fire severities and study sites. Chi-square tests show significant increases (p < 0.05) in water repellency for surface soils (0 mm) after burning at Upper Yarra and Mt Cole. There were no significant differences in water repellency between: high and low severity at Upper Yarra and Big Ben, burnt and unburnt surface soils at Big Ben, and burnt and unburnt sub-surface soils at all sites.

(a) Upper Yarra



(b) Big Ben



(c) Mt Cole

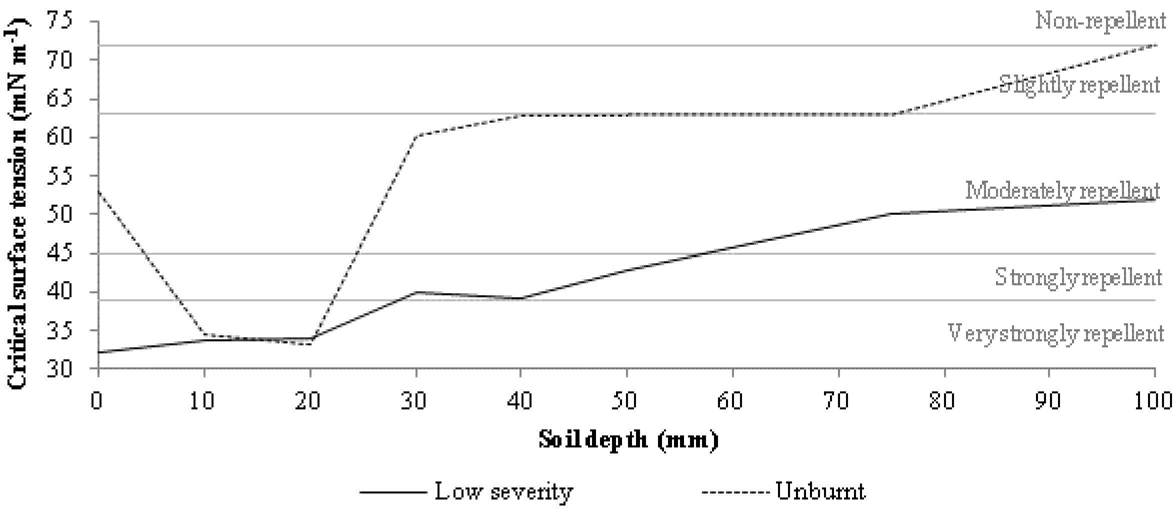


Figure 28: Median critical surface tensions less than 2 months after burning as a function of depth at (a) Upper Yarra, (b) Big Ben and (c) Mt Cole.

4.3.3 Relationship between soil heating and soil water repellency

At Upper Yarra there was a statistically significant relationship between surface soil heating and surface water repellency (Figure 29) (Chi-square test; $p < 0.05$). Higher soil temperatures were associated with more widespread water repellency even when the temperatures exceeded thresholds associated with the destruction of water repellency in laboratory studies (i.e. 280 ^{o}C; DeBano 2000). There were no statistically significant relationships between water repellency and temperature at Mt Cole and Big Ben.

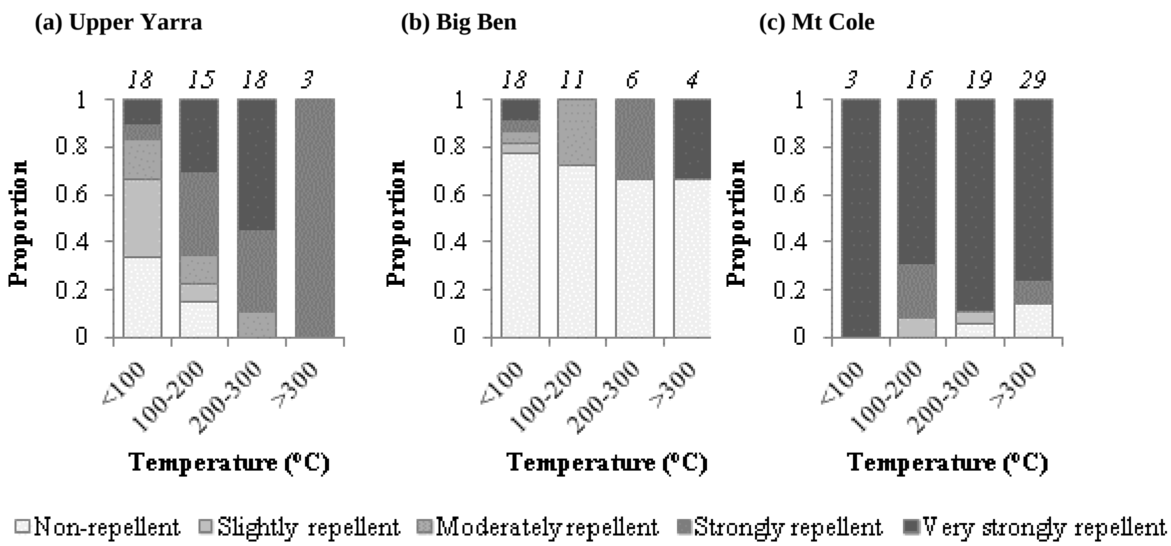


Figure 29: Surface soil water repellency immediately post-burn as a function of surface temperature. Numbers above each column are the sample sizes.

4.3.4 Seasonal trends and post-fire recovery

The proportion of water repellent points – i.e. points that were at least slightly repellent (CST < 62.9 mN m^{-1}) – at the soil's surface (0-20 mm) in unburnt soils at Upper Yarra oscillated seasonally, with stronger repellency in autumn compared with spring (Figure 30). In terms of median CSTs, these seasonal oscillations were only apparent for soils beneath the soil surface as shown in Figure 31 for 20 mm deep soils.

Burning resulted in smaller seasonal oscillations in the proportion of water repellent sampling points at Upper Yarra relative to unburnt soils (Figure 30). There were significantly more water repellent sampling points in burnt areas compared with unburnt areas in spring but not autumn (with the exception of the first measurements post-burn) (chi-square tests; $p < 0.05$). In terms of median CSTs, there were no apparent changes to the seasonal oscillations after burning (Figure 31). Seasonal trends in water repellency and differences between burnt and unburnt areas were associated with seasonal trends in soil moisture contents (Appendix 11). The data from Big Ben showed no significant differences in water repellency between burnt and unburnt areas in spring or autumn (Figure 30 and Figure 31), while the data from Mt Cole showed large differences in surface water repellency between burnt and unburnt areas in both spring and autumn.

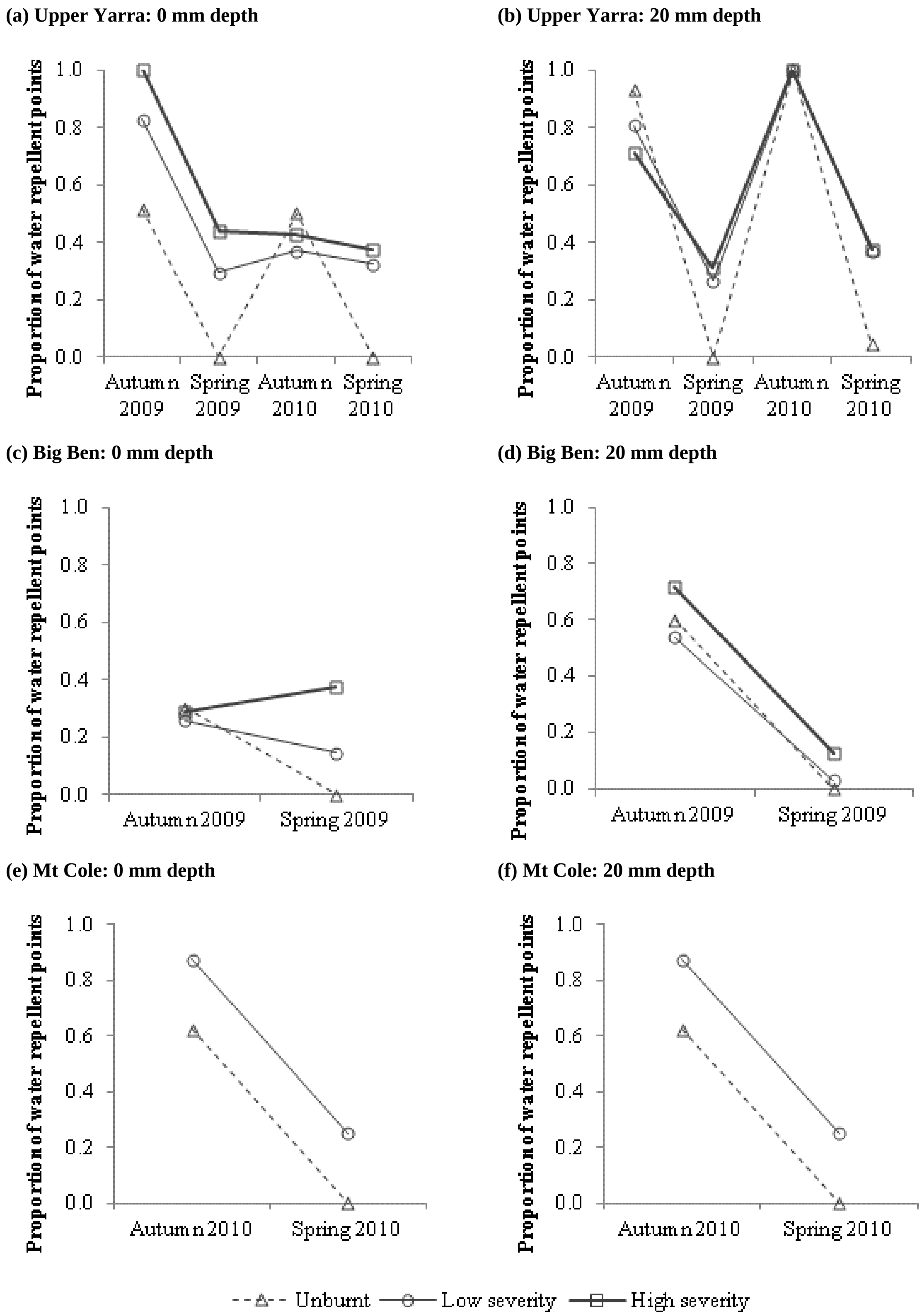


Figure 30: Proportion of water repellent sampling points (≥ slightly repellent) for each measurement date and fire severity.

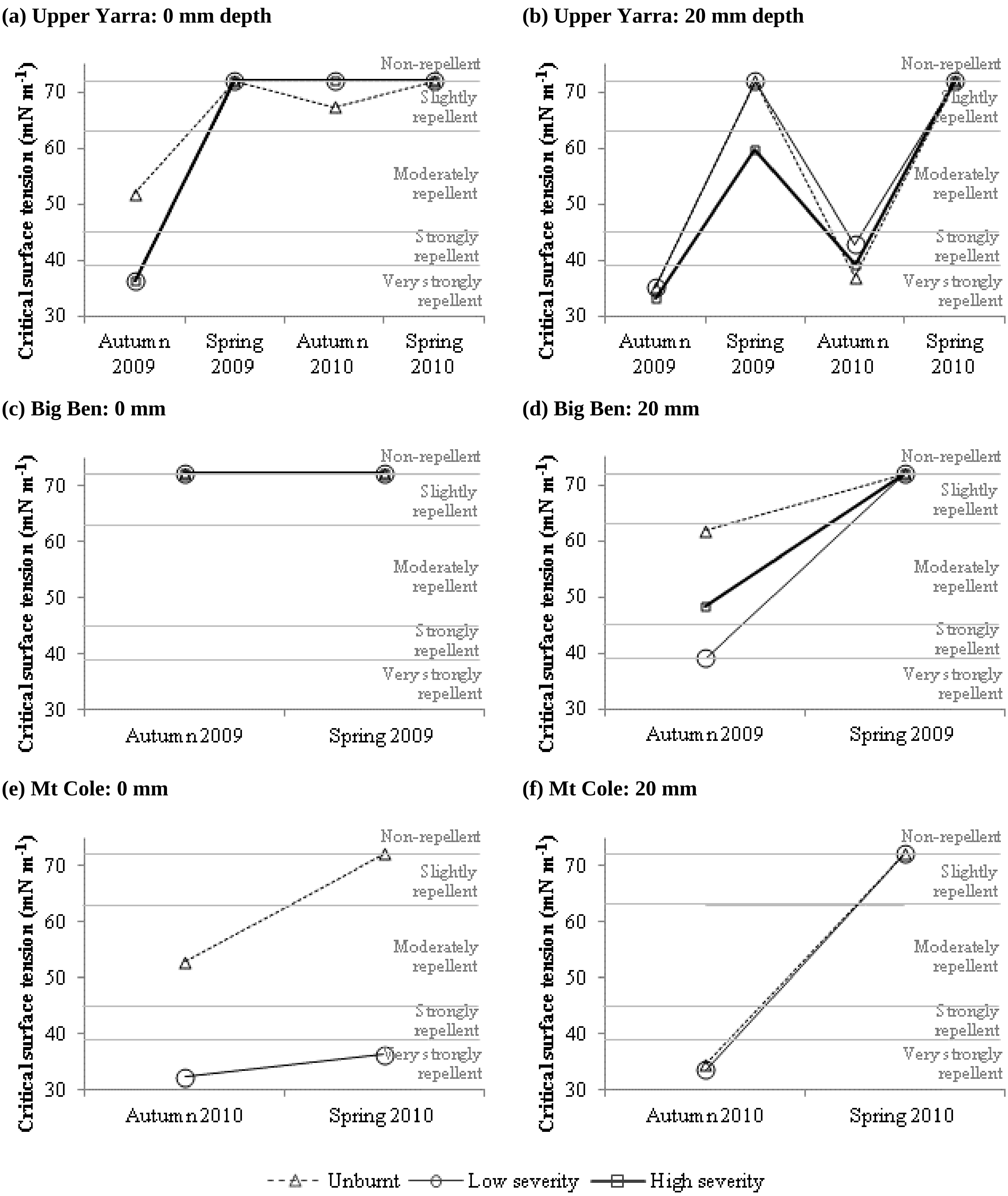


Figure 31: Median critical surface tensions (mN m^{-1}) for different seasons and depths in unburnt, low severity and high severity areas at Upper Yarra, Big Ben and Mt Cole.

4.4 Discussion

Relationships between fire severity, soil heating and soil water repellency were examined using field data collected from three sites. Several hypotheses were addressed and the outcomes in relation to those hypotheses are described in Table 15.

Table 15: A summary of the results in relation to each hypothesis

Hypothesis	Outcome	Description
Prescribed burning changes soil water repellency (Hypothesis A)	Partially accepted	Soil water repellency increased following burning at Upper Yarra and Mt Cole (Figure 27 and Figure 28) but not at Big Ben.
Changes to soil water repellency following prescribed burning are related to the fire severity (Hypothesis A1)	Rejected	There were no significant differences in soil water repellency between the high and low fire severities at Upper Yarra and Big Ben (Figure 27 and Figure 28).
Soil water repellency recovers fully within 18-months of prescribed burning (Hypothesis A2)	Rejected	Water repellency decreased in burnt areas in the first six months post-burn, but remained stronger than in unburnt areas at Upper Yarra and Mt Cole. For the remainder of the 18-month measurement period at Upper Yarra water repellency was stronger in burnt compared with unburnt areas in spring but not autumn (Figure 30).

4.4.1 Links between fire severity and soil heating

Surface (0 mm) temperatures were significantly higher in the high fire severity areas (50% points > 200 ^{o}C) compared with the low fire severity areas (19% points > 200 ^{o}C) at Upper Yarra. Other studies also report higher surface temperatures in high compared to low fire severity areas (e.g. DeBano *et al.* 1979; Hartford and Frandsen 1992; Vadilonga *et al.* 2008; Vega *et al.* 2005; Williams *et al.* 2004). The mean surface temperature in the low severity areas at Upper Yarra was 134 ^{o}C, which is within the wide range of mean temperatures reported elsewhere for low fire severities (see Table 2 in Chapter 2). For example, Vega *et al.* (2005) reported 37 ^{o}C and Vadilonga *et al.* (2008) reported 190-200 ^{o}C in shrubland, Hartford and Frandsen (1992) reported 400 ^{o}C in mixed-conifer forests and DeBano *et al.* (1979) reported 249 ^{o}C in chaparral. Similarly, the mean surface temperature in the high severity area at Upper Yarra (228 ^{o}C) was within the range of temperatures reported by others for high fire severities. For example, Vega *et al.* (2005) reported 73 ^{o}C and Vadilonga *et al.* (2008) reported > 400 ^{o}C in shrubland, Hartford and Frandsen (1992) reported < 80

^{o}C in mixed-conifer forests, Fernández *et al.* (2008) reported 209 ^{o}C in mixed heathland, and DeBano *et al.* (1979) reported 691 ^{o}C and Odion and Davis (2000) reported 775-925 ^{o}C in chaparral.

Sub-surface temperatures were generally low with mean temperatures of 79 ^{o}C and 55 ^{o}C at depths of 10-20 mm for the high and low severity areas, respectively, and there were no statistically significant differences in sub-surface temperature between the severities at Upper Yarra. Most other studies also report low temperatures below the soil surface and little difference in sub-surface temperatures between high and low fire severities (e.g. Fernández *et al.* 2008; Vadilonga *et al.* 2008; Vega *et al.* 2005).

While the areas of low fire severity had similar appearances at each site (generally a patchy burnt for the surface fuels, scorched understorey and unburnt canopy) there were differences in the temperatures observed (Figure 32). Mean temperatures were higher at Mt Cole compared with Upper Yarra and Big Ben (Figure 25). For example, the mean surface temperature at Mt Cole in the low severity area was comparable to the mean surface temperature at Upper Yarra in the high severity area. These differences in temperatures between the sites could reflect differences in the amount of fuel consumed, since the mass of surface fuel consumed at Mt Cole was slightly higher than at the other sites (Table 12 in Chapter 3). Another factor could be the type of fuel consumed (as discussed by Bradstock *et al.* 1992). Heavier fuels such as bark and litter, which occurred in larger quantities at Mt Cole, produce higher temperatures than lighter, grassy fuels (Bradstock *et al.* 1992). Other studies also report a range of temperatures for the same fire severity classes (e.g. DeBano *et al.* 1979; Fernández *et al.* 2008; Hartford and Frandsen 1992; Vadilonga *et al.* 2008; Vega *et al.* 2005), suggesting that while fire severity is a good indicator of relative differences in soil heating within a site, it is not a reliable predictor of absolute temperature.

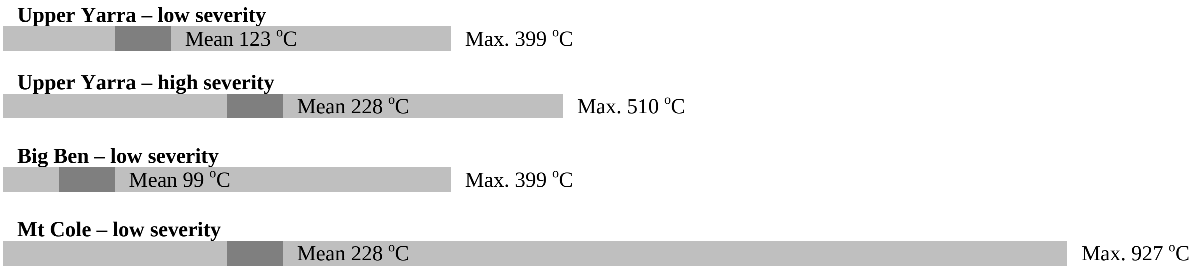


Figure 32: Scales bars to illustrate differences in the mean and maximum surface temperatures at each study site as measured using the pyrometers. The minimums were all 20^{o}C.

4.4.2 Soil water repellency in unburnt areas

Soil water repellency was widespread in unburnt areas at all three study sites with 30-56% of points at least slightly repellent at the surface. Other studies also report water repellent soils in dry eucalypt forests, suggesting that soil water repellency is a common feature of this forest type (Doerr *et al.* 2004; Doerr *et al.* 2006; Nyman *et al.* 2010b). At Upper Yarra, Big Ben and Mt Cole the strength of water repellency decreased with depth and soils were generally non-repellent at depths > 75 mm (Figure 28).

4.4.3 Effects of burning on soil water repellency

Surface soil water repellency was strengthened following burning at Upper Yarra and Mt Cole, but not at Big Ben (Figure 27 and Figure 28). The absence of an effect at Big Ben could reflect shorter heating durations (mean durations > 175 ^{o}C were 1.2 min, 7.4 min and 10.3 min at Big Ben, Upper Yarra and Mt Cole, respectively; Figure 26b) and slightly lower mean temperatures during the burn (mean surface pyrometer temperatures were 123 ^{o}C, 99 ^{o}C and 228 ^{o}C for low severity areas at Upper Yarra, Big Ben and Mt Cole, respectively; Figure 25). The shorter heating durations and lower mean temperatures at Big Ben compared with the other sites may reflect the predominately grassy surface fuels, which have been found to have shorter residence times than leaf litter (Bradstock *et al.* 1992).

Increased soil water repellency at Upper Yarra and Mt Cole following burning is in agreement with results from several other studies, which found that water repellency increased in burnt areas (Table 3 in Chapter 2) (e.g. Huffman *et al.* 2001; Robichaud 2000; Vadilonga *et al.* 2008; Woods *et al.* 2007). In contrast to those studies, Doerr *et al.* (2006) reported a decrease in water repellency at the soil surface and an intensification of water repellency beneath the soil surface following a wildfire in the Sydney sandstone region of NSW, Australia. These soils exhibited pre-existing soil water repellency and Doerr *et al.* (2006) suggested that steep temperature gradients in the soil profile during the fire caused water repellency to migrate down the soil profile (it was destroyed at the surface by the highest temperatures and enhanced beneath the surface where heating was less intense). The absence of a similar effect at Upper Yarra, Big Ben and Mt Cole, despite pre-existing soil water repellency (Figure 27) and temperatures sometimes above the thresholds required to destroy water repellency (Figure 26a), could reflect the short duration of heating at high temperatures (1.2 - 10.3 min at temperatures > 175 ^{o}C and 0.2 – 3.7 min at temperatures > 280 ^{o}C; Figure 26b).

4.4.4 Effects of fire severity on soil water repellency

There were no significant differences in water repellency between the low and high fire severity areas at Upper Yarra and Big Ben (i.e. chi-square tests showed no significant differences between the severities; Figure 27). Measurements at Mt Cole were only conducted in unburnt and low severity areas, hence no fire severity comparison could be made. This is a surprising result at Upper Yarra since temperatures were significantly hotter in the high (mean of 228 ^{o}C) compared with the low (mean of 123 ^{o}C) severity areas, and when the water repellency data were analysed as a function of temperature without grouping by severity class, higher temperatures were associated with greater water repellency (Figure 29a). It appears that while differences in temperature between the fire severities at Upper Yarra were statistically significantly different, they were not sufficiently consistently different to cause detectable differences in water repellency. This is illustrated in Figure 25, where the error bars for the mean pyrometer temperatures are wide and overlapping for the low and high severity areas at Upper Yarra. Some other studies report larger differences between low and high severity areas in terms of changes to water repellency (e.g. Doerr *et al.* 2006; Robichaud 2000;

Vadilonga *et al.* 2008). However, even for those studies, post-fire changes to water repellency are often not statistically significant (e.g. Robichaud 2000; Vadilonga *et al.* 2008).

4.4.5 **Seasonal trends and post-fire recovery**

Water repellency diminished in the first six months after burning at the Upper Yarra with 83-100% of points at the surface being water repellent in autumn 2009 compared with only 30-44% the following spring (Figure 30). Following this initial decline, the proportion of water repellent points remained relatively constant in the burnt areas, while it fluctuated seasonally in the unburnt areas at Upper Yarra. This meant that significant differences in water repellency between burnt and unburnt areas only occurred in spring (with the exception of the first measurements post-burn). Similar results were reported by Sheridan *et al.* (2007) in wet eucalypt forest following a wildfire. They found that water repellency in burnt soils persisted through the first winter after the fire while in unburnt soils it diminished. The absence of seasonal fluctuations in water repellency in burnt areas was associated with lower soil moistures in winter/spring in burnt areas compared with unburnt areas at Upper Yarra, presumably because of a lack of vegetation and litter enabling the soil to dry more rapidly (Appendix 11).

As mentioned above, at Upper Yarra there was no further evidence of diminishing water repellency in burnt areas relative to unburnt areas after the initial decline during the first six months post-burn (Figure 30). At Mt Cole water repellency remained stronger in burnt areas relative to unburnt areas six-months post-burn (Figure 31). These results suggest that while the effects of prescribed burning on water repellency diminish over 18-months, total recovery takes longer. Doerr e*t al.* (2006) and Huffman *et al*. (2001) found that fire-induced water repellency persisted for more than two-years and 22-months, respectively; in contrast, MacDonald and Huffman (2004) reported a shorter recovery time of just one year. Factors likely to affect post-fire recovery of water repellency include the magnitude and type of changes to water repellency that occurred as a result of burning (Doerr *et al.* 2006; MacDonald and Huffman 2004), rates of vegetation recovery and post-fire climatic conditions; the latter two factors affect soil moisture.

4.5 Conclusion

Soils were water repellent in the absence of fire and prescribed burning increased soil water repellency in some, though not all, instances. Site characteristics such as the soil moisture during the burn, the predominant surface fuel type (bark, litter or grass) and fuel load are likely to have determined the extent of soil heating and fire-induced changes to water repellency. Differences in soil texture did not appear to affect fire-induced changes to soil water repellency. Fire severity was not related to changes in soil water repellency, despite differences in mean soil temperatures between the low and high severity areas at Upper Yarra. It appeared that while differences in temperature between the fire severities were statistically significantly different, they were not sufficiently consistently different to cause detectable differences in water repellency. Although fire-induced water repellency diminished in the first six months following burning at Upper Yarra, a full recovery to pre-fire levels was not achieved within 18-months. Seasonal fluctuations in water repellency in unburnt areas resulted in more water repellency in burnt relative to unburnt areas in spring, but not autumn.

5. Effects of prescribed burning on point-scale infiltration

This chapter quantifies the effects of fire severity on soil infiltration capacities at the point-scale using mini-disk ponded and tension infiltrometers at Upper Yarra, Big Ben and Mt Cole.[2]

5.1 Introduction

Soil infiltration capacity – the maximum volume of water that can enter a unit area of the soil surface per unit time for a given hydraulic head (2004) – is determined by a number of factors including the soil texture, structure, porosity, water repellency and organic matter on the soil surface (Neary *et al.* 2009). It is distinguished from the infiltration rate, which is the actual rate of water uptake for a given rainfall intensity (Hawkins and Cundy 1987). Forest soils typically have high infiltration capacities compared to other soil types (Neary and Ffolliott 2008; Neary *et al.* 2009). Plant roots and faunal burrowing create macropores in forest soils, enabling rapid infiltration under saturated conditions (Beven and Germann 1982). Organic matter in the soil increases the stability of soil aggregates while leaf litter on the soil surface dissipates raindrop energy and facilitates infiltration (Neary and Ffolliott 2008; Neary *et al.* 2009).

Fire is thought to reduce infiltration capacities through its effects on soil water repellency and vegetative cover (e.g. Certini 2005; Neary *et al.* 1999; Shakesby 2011; Shakesby and Doerr 2006; Shakesby *et al.* 2007). Changes to soil water repellency and vegetative cover are sometimes associated with the fire severity (Benavides-Solorio and MacDonald 2005; Doerr *et al.* 2006), and hence fire severity may be an important indicator of changes to soil infiltration capacities (Neary *et al.*

[2] Note: some of the ponded and tension infiltrometer measurements collected immediately post-burn (n=54) and 6-months post-burn (n=54) at Upper Yarra were collected by Akiko Oono.

1999; Shakesby and Doerr 2006). Therefore, this chapter examines the effects of fire severity on infiltration capacity at the point-scale (15 cm^2). The following hypotheses are addressed:

- Prescribed burning reduces infiltration (Hypothesis B)
- Decreases in infiltration capacities following prescribed burning are related to the fire severity (Hypothesis B1)
- Infiltration capacities recover fully within 18-months of prescribed burning (Hypothesis B2)

Ponded and tension infiltrometers were used to measure the infiltration capacity at Upper Yarra, Big Ben and Mt Cole[3]. They had relatively small disk sizes (45 mm diameter) to reduce potential bias associated with having to select a relatively flat surface on which to perform the infiltration. There are several advantages of using constant head infiltrometers (Table 16). Firstly, they provide a direct measure of infiltration capacity, whereas other methods such as rainfall simulations or runoff plots only measure the *apparent* infiltration rate, which may be less than the infiltration capacity. Secondly, the water entry pressure head is precisely controlled, which means that the contribution of different pore sizes classes to the infiltration capacity can be assessed (e.g. Nyman *et al.* 2010a). The constant head also enables the same measurements to be repeated in different locations. Other advantages of infiltrometers are that they are easy to use, cheap to purchase and highly portable, allowing measurements to be done in inaccessible locations by many people. A potential disadvantage of infiltrometers with small disks is that they are impractical for measuring infiltration capacities within larger holes, which means they may underestimate plot and hillslope-scale infiltration capacities. To partially compensate for this, the density and approximate infiltration capacities of surface depressions and holes (caused by bioturbation, roots and soil cracking) were also determined as part of the study. A further disadvantage of infiltrometers is that they do not simulate the effects of raindrop energy on infiltration.

[3] As mentioned previously, the infiltration capacity is the maximum volume of water that can enter a unit area of the soil surface per unit time for a given hydraulic head. It is distinct from the infiltration rate, which is the actual rate of water uptake for a given rainfall intensity.

Table 16: Advantages and disadvantages of constant head infiltrometers

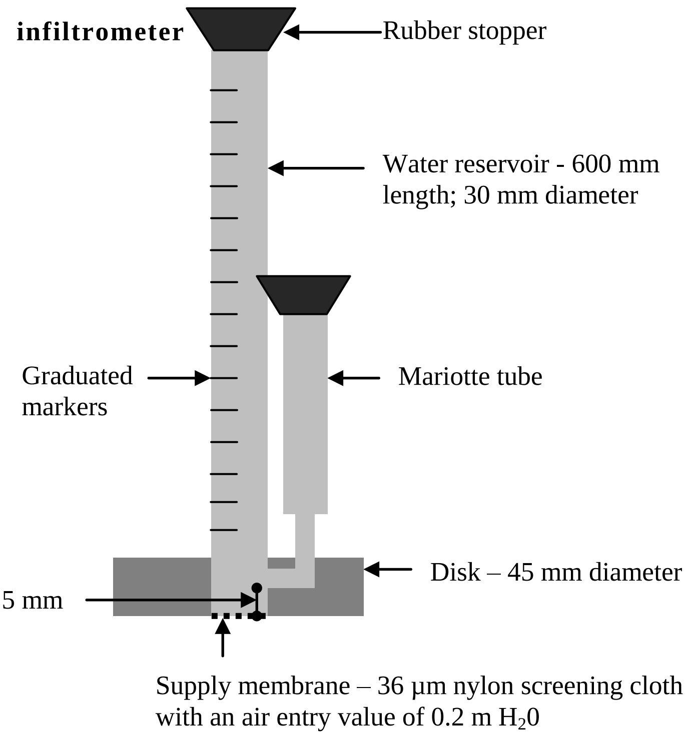
Advantages	Disadvantages
Direct measurement of infiltration capacity.	May not capture the effect of larger macropores or hollows.
Water entry pressure head is precisely controlled.	No simulation of the effects of raindrop energy on infiltration.
Minimal equipment and technical skills required.	
Highly portable.	

5.2 Methods

5.2.1 Infiltrometer measurements

Soil infiltration capacity was measured using mini-ponded and mini-tension infiltrometers with disk diameters of 45 mm. The ponded infiltrometer was custom-made based on designs by Nyman *et al.* (2010) and Perroux and White (1988). The tension infiltrometer was designed and built by Decagon Devices (Figure 33).

(a) Cross-sectional view of mini-ponded infiltrometer **(b) Mini-tension infiltrometer**



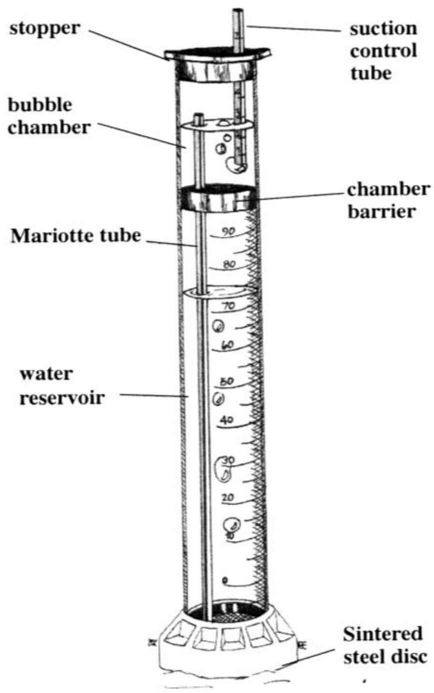


Figure 33: Designs of the (a) mini-ponded infiltrometer and (b) mini-tension infiltrometers.

The infiltrations were performed within 2-6 weeks of the burns (in autumn) and then six-months post-burn (in spring) at all sites to assess the immediate effects of the burn and early recovery. Additional measurements at Upper Yarra were performed 12-months post-burn (in autumn) and 18-months post-burn (in spring) to provide a longer sequence of post-fire effects. All infiltrations were done within 1 m of the sampling points described in Chapter 3, on an undisturbed patch of soil that appeared to be representative of the broader areas. Rocks, surface depressions, hollows, ant mounds and other faunal diggings were avoided (Figure 34).

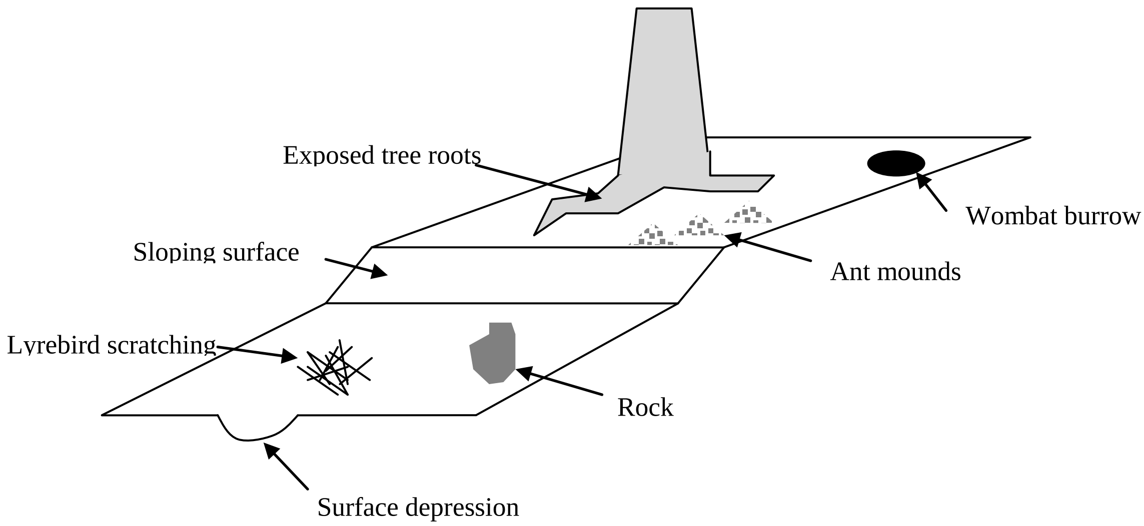


Figure 34: Areas excluded from sampling with the ponded and tension infiltrometers.

For points in unburnt areas the surface litter was removed with a brush, while for points in burnt areas the ash was retained. The inside of a metal ring (70 mm diameter) was coated with petroleum jelly before it was inserted 30 mm into the ground (Figure 35). The petroleum jelly prevented preferential flow down the side of the ring during the infiltration measurements. Uneven soil surfaces were smoothed by sprinkling a small amount of sand onto the surface. A stand and clamp held the infiltrometers in the centre of the ring during the infiltrations. The tension infiltration was performed first (hydraulic head of -20 mm) followed by the ponded infiltration (hydraulic head of + 5 mm). For both measurements the depth of water in the reservoir was recorded at 30-second intervals until the rate of infiltration was constant.

(a) Ponded infiltrometer

(b) Tension infiltrometer

Figure 35: The ponded and tension infiltrometers set-up at sampling points in the field.

5.2.2 **Survey of surface holes and depressions at Upper Yarra**

A survey of surface holes and depressions (> 50 mm diameter) was conducted at Upper Yarra in January 2010 to provide insight into their effect on hillslope-scale infiltration capacities. The holes/depressions were predominantly caused by bioturbation (there was evidence of wombats and bandicoots at the site), roots and soil cracks (Figure 36). The location of every hole or depression was recorded within belt transects (50 m long x 2 m wide) running perpendicular to the slope. There were six transects per fire severity treatment (unburnt, low severity and high severity). The holes/depressions were photographed for future reference. Additionally, the infiltration capacity was approximated for ten randomly selected holes by pouring 500 mL of water into the hole and recording the length of time required for that water to infiltrate.

Figure 36: Photographs to illustrate the appearance of some of the surface holes and depressions

5.2.3 Data analysis

The data were analysed assuming a completely randomised design rather than the originally intended randomised block design. As explained in Chapter 3, this was due to the unbalanced nature of the sampling design after burning. Steady-state infiltration capacities under tension (- 20 mm) and ponded (+ 5 mm) conditions were calculated from the gradient of the straight-line portion of a plot of cumulative infiltration (mm) against time (h). Frequency histograms of the steady-state rates showed that the data were strongly skewed with many zero values. Therefore, non-parametric Mann Whitney tests were used to test for statistically significant differences between treatments and seasons. The survey data of surface holes and depressions were summarised by calculating the densities (per 100 m^2) for each belt transect and then averaging those results as a function of burn treatment (unburnt, low severity and high severity). T-tests were used to determine the statistical significance ($p < 0.05$)

of differences between the mean densities of surface holes/depressions (histograms of the data were approximately normally distributed).

5.3 Results

5.3.1 Infiltrometer measurements

Prescribed burning appeared to have little effect on ponded and tension steady-state infiltration capacities compared with unburnt values (Figure 37). Differences in steady-state infiltration capacities between the treatments (unburnt, low severity and high severity) were generally non-significant with the exception of the ponded infiltration measurements in autumn 2010 at Upper Yarra (Figure 37a), the tension infiltrometer measurements in spring 2009 at Upper Yarra (Figure 37b), and the tension infiltrometer measurements in autumn 2010 at Upper Yarra (Figure 37b) and Mt Cole (Figure 37f). At Upper Yarra, infiltration capacities were significantly higher in spring than autumn (Figure 37a). There were also significant differences between years for the same season. For example, median infiltration capacities were significantly lower in autumn 2009 compared with autumn 2010 at Upper Yarra (Figure 37a), which potentially reflects drier weather in 2009 (Figure 17 in Chapter 3). Steady-state ponded infiltration capacities were highly skewed (Appendix 12) and had large variances within a fire severity treatment (Appendix 13). For example, at Upper Yarra in autumn 2009 the coefficients of variation were 201%, 248% and 277% for unburnt, low severity and high severity, respectively.

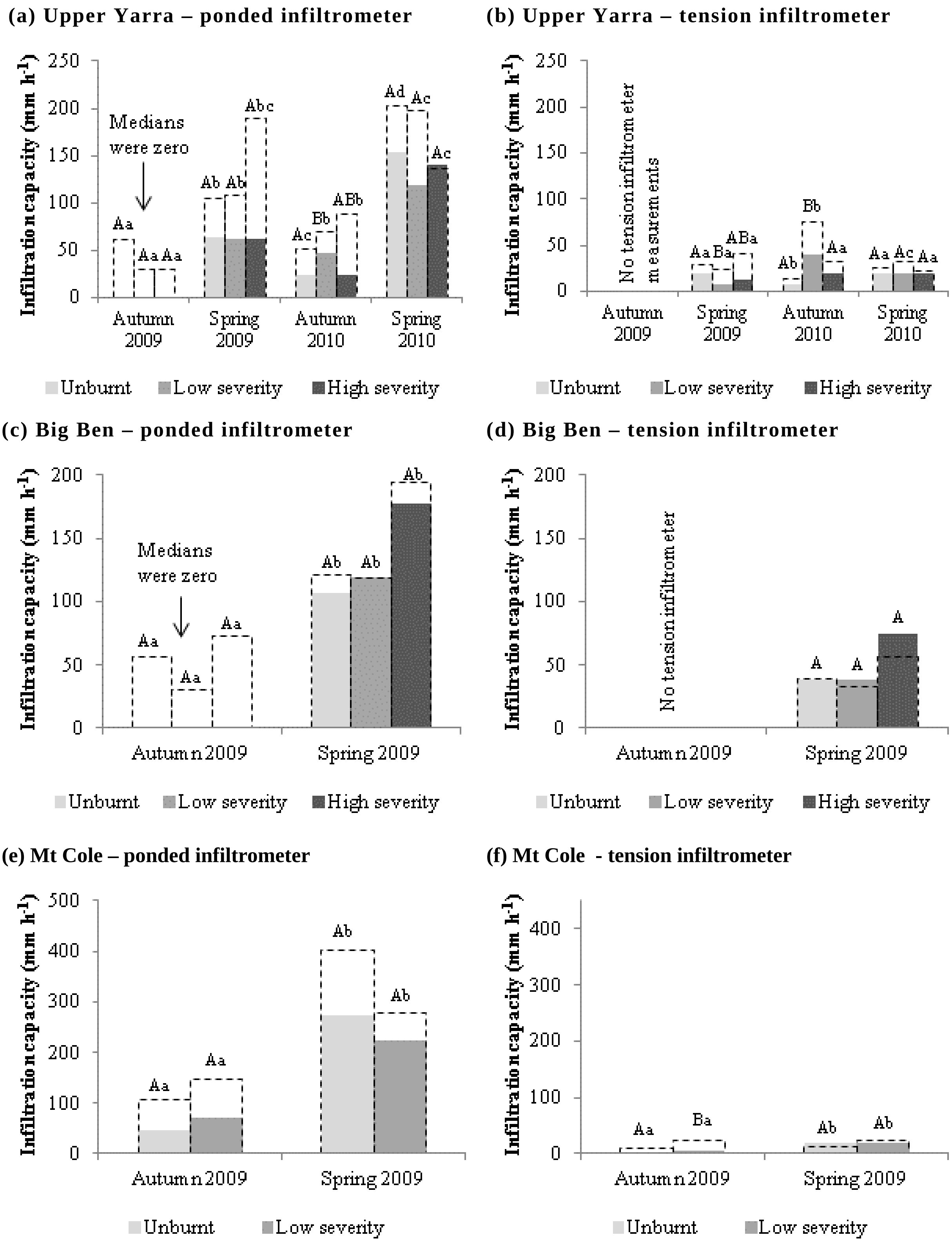


Figure 37: Infiltration capacities measured with ponded and tension infiltrometers for unburnt, low and high severity areas in spring and autumn following burning at Upper Yarra, Big Ben and Mt Cole. The tops of the shaded bars denote median values and those of the dotted lines denote mean values. Upper case letters denote the outcome of Mann Whitney tests between treatments (unburnt, low and high severity) on the same measurement date. Lower case letters denote the outcome of Mann Whitney tests between measurements dates for the same treatment. Non-significant differences (i.e. *p* > 0.05) have the same letter while sigificant differences (i.e. *p* < 0.05) have different letters.

5.3.2 Survey of surface holes and depressions

The density of surface holes and depressions (> 50 mm diameter) at Upper Yarra was significantly ($p < 0.05$) greater in unburnt areas compared with burnt areas (Figure 38). In unburnt areas there were 25 holes / depressions per 100 m^2; assuming these holes / depressions were 50 mm wide (the minimum size recorded), this would equate to one hole / depression intersecting the flow path every 80 m. The approximate infiltration capacities of 10 randomly selected holes were high overall and highly variable, with a mean of 9890 mm h^{-1} and a standard deviation of 13272 mm h^{-1}.

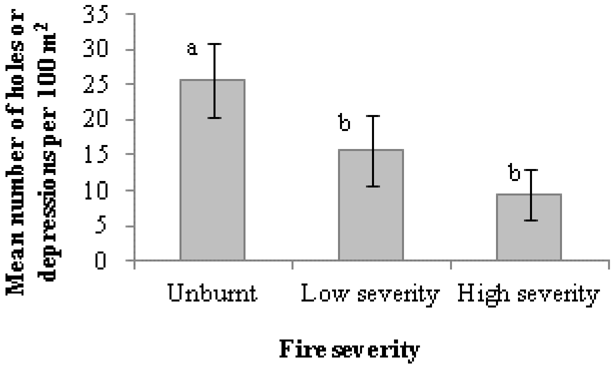


Figure 38: Mean density of surface holes and depressions (> 50 mm diameter) in unburnt, low severity and high severity areas at Upper Yarra in January 2010. Letters denote the outcome of statistical testing between the means (t-tests). Means with the same letter were not statistically significantly different. The holes / depressions were caused by bioturbation, soil cracking and root holes.

5.4 Discussion

The effect of prescribed burning on soil infiltration capacity at the point-scale was examined using ponded and tension infiltrometers. The outcomes in relation to the hypotheses are described in Table 17. Since Hypothesis B was rejected, Hypotheses B1 and B2 were no longer applicable to the data.

Table 17: A summary of the results in relation to each hypothesis

Hypothesis	Outcome	Description
Prescribed burning reduces infiltration (Hypothesis B)	Rejected	There were no significant differences between the median steady state infiltration capacities measured in unburnt, low severity and high severity areas.
Decreases in infiltration capacities following prescribed burning are related to the fire severity (Hypothesis B1)	Not applicable	Prescribed burning had no apparent effect on infiltration, and therefore this hypothesis was not applicable to the data
Infiltration capacities recover fully within 18-months of prescribed burning (Hypothesis B2)	Not applicable	Prescribed burning had no apparent effect on infiltration, and therefore this hypothesis was not applicable to the data.

Despite differences in the median infiltration capacities between the sites (with higher median values at Mt Cole as a result of its sandy soil), the infiltration capacities were very low overall in both burnt and unburnt areas, especially in autumn. During the first autumn of measurements, mean values in unburnt areas ranged from 56 mm h^{-1} to 108 mm h^{-1} (for + 5 mm hydraulic head) (Appendix 13), infiltration histograms were strongly positively skewed (Appendix 12) and there were numerous points of zero infiltration (Appendix 13). Few studies have used infiltrometers to measure infiltration in dry eucalypt forests (exceptions include Nyman *et al.* 2010b; Nyman *et al.* 2011). Using the same ponded infiltrometers as this study, Nyman (2010b) reported very low infiltration capacities (mean < 30 mm h^{-1}) in recently wildfire-burnt dry eucalypt forests with clay-loam soil in July 2009 while in a similar catchment burnt three years earlier he measured much higher infiltration capacities (mean ~ 400 mm h^{-1}). The low infiltration capacities reported by Nyman *et al.* (2010b) together with the results from Upper Yarra, Big Ben and Mt Cole, suggest that low infiltration capacities are a common feature of dry eucalypt forests.. In contrast, much higher infiltration capacities are reported for wet eucalypt forests (Sheridan *et al.* 2007).

Seasonal fluctuations in the infiltration capacity were apparent at Upper Yarra, with higher capacities in spring compared with autumn (Figure 37). Over six-months at Big Ben and Mt Cole, infiltration capacities increased from autumn to spring, suggesting that seasonal fluctuations also existed at these sites. Seasonal fluctuations in infiltration capacities are likely to be caused by seasonal fluctuations in soil water repellency (Chapter 4), and as mentioned in Chapter 4, seasonal fluctuations in soil water repellency are likely to be caused by seasonal fluctuations in soil moisture.

Surprisingly, steady-state infiltration capacities were not significantly different between burnt and unburnt areas despite increased soil water repellency in burnt areas (Chapter 4). Similarly, Sheridan *et al.* (2007) found no significance differences in infiltration capacities (measured with a ponded infiltrometer) between burnt and unburnt areas in wet eucalypt forests, despite higher levels of water repellency in the burnt areas. At Upper Yarra, these results suggest that seasonally-induced changes to water repellency affect infiltration capacities differently to fire-induced changes to water repellency. Some potential explanations are that:

- seasonally-induced changes to water repellency were more substantial than fire-induced changes. For example, at Upper Yarra differences in median critical surface tensions (CST) between seasons were slightly larger (20 mN m^{-1}) than differences between burnt and unburnt areas (16 mN m^{-1}) (Table 7 in Chapter 4).
- the sensitivity of infiltration capacity to changes in water repellency depends on the range of CST values over which that change occurs. At Upper Yarra the median CST changed from 52 mN m^{-1} to 72 mN m^{-1} between autumn and spring, and from 36 mN m^{-1} to 52 mN m^{-1} between burnt and unburnt (Table 7 in Chapter 4). Perhaps infiltration capacities are more greatly affected by water repellency when the changes to water repellency occur at the upper end of the range of CST values.

As discussed in the introduction and methods sections of this chapter (Table 16 and Figure 34), infiltrometers are limited in their ability to capture the full range of infiltration capacities occurring across a site. Surface holes and depressions are a potential source of infiltration not reflected in the infiltrometer measurements. As shown in this study, these holes / depressions (> 50 mm in diameter) may sometimes have very high infiltration capacities compared to the surrounding area (a mean capacity of 9890 mm h^{-1} was measured at Upper Yarra). The mechanism causing these higher infiltration capacities is not known. Potentially the hole / depression provides a bypass route through the otherwise water repellent topsoil; alternatively it may connect to root holes that provide a conduit for rapid infiltration. Other studies report higher infiltration in 'foraging pits' created by a range of native fauna (Eldridge and James 2009; Garkaklis *et al.* 1998). In Western Australia, Garkaklis *et al.* (1998) measured a sharp decrease in water repellency within the foraging pits of the brush-tailed bettong (*Bettongia penicillata*) compared with surrounding areas, and observed evidence of preferential infiltration within these pits during rainfall. Lyrebirds may also play a role in disturbing the water repellent topsoil. They are known to cause widespread soil disturbance as a result of their foraging (Ashton and Bassett 1997), and were observed at Upper Yarra. Importantly, these holes / surface depressions were found to occur more frequently in unburnt areas at Upper Yarra, presumably reflecting that there was more shelter for foraging animals in unburnt areas. These results suggest that surface holes / depressions are a potentially important factor influencing infiltration capacity and runoff at the hillslope-scale, with one hole / depression intercepting a flow path at least every 80 metres on an unburnt hillslope.

5.5 Conclusion

Fire-induced soil water repellency had no significant effect on infiltration capacities at the point-scale at all three study sites, irrespective of soil texture and other differences between the sites. In contrast, seasonal fluctuations in median infiltration capacities were often statistically significant with infiltration capacities generally lower in autumn than in spring. These results suggest that fire-induced changes to soil water repellency affect infiltration capacities differently to seasonally-induced changes and overall, prescribed burning has little effect on point-scale infiltration capacities. Surface holes and depressions (> 50 mm diameter) were found to occur more frequently in unburnt areas. Very high mean infiltration capacities within these holes / depressions suggest that they may significantly affect infiltration at hillslope and possibly catchment scales.

6. Effects of prescribed burning on plot-scale runoff and erosion

This chapter quantifies the effects of fire severity on infiltration, runoff and erosion at the plot-scale using rainfall simulations on 3 m^2 plots at Upper Yarra.

6.1 Introduction

There are two types of surface runoff (or overland flow) – infiltration-excess (or Hortonian) overland flow and saturation-excess overland flow (Rose 2004). The former occurs when rainfall rates exceed the infiltration capacity of the soil, while the latter occurs when the soil is saturated and hence there is no soil pore space available for surface water to infiltrate. In undisturbed forests, surface runoff occurs infrequently and mostly via saturation overland flow in low lying areas such as floodplains, wetlands, ephemeral streams and riparian zones near permanent streams (Neary and Ffolliott 2008; Neary *et al.* 2009). The horizontal extent of the saturated zone varies seasonally and during a rainfall event (as described by Neary *et al.* 2009; Rose 2004). Infiltration-excess overland flow may occur during very intense storms or on degraded soils where a soil seal has formed or compaction has occurred (e.g. on logging tracks) (Neary *et al.* 2009; Rose 2004). Fire is thought to increase rates of infiltration-excess overland flow in forests by increasing soil water repellency and reducing vegetative cover (as reviewed by Certini 2005; Neary *et al.* 1999; Shakesby and Doerr 2006; Shakesby *et al.* 2007). Fire severity is a potential indicator of the extent of these changes to infiltration-excess overland flow (Benavides-Solorio and MacDonald 2001; Robichaud 2000).

Surface erosion by water is caused by raindrop impact and surface runoff, although in undisturbed forests it rarely occurs as vegetation protects the soil surface from raindrop impact and surface runoff is uncommon (Rose 2004; Wondzell and King 2003). Raindrop impact causes erosion on a bare soil surface by dislodging soil particles into the surface water and breaking down the soil structure, resulting in soil sealing, lower infiltration rates and thus more runoff (Rose 2004). Surface runoff causes erosion when the depth and flow rate (stream power) exceed threshold values; this flow-driven erosion is most pronounced on steeper slopes and at larger spatial scales (Rose 2004). The primary factors contributing to increased erosion in burnt areas are the availability of readily erodible sediment (and ash), the loss of vegetative cover and changes to soil-infiltration rates (Wondzell and King 2003). These factors may be linked to the fire severity (as demonstrated by Benavides-Solorio and MacDonald 2001; Benavides-Solorio and MacDonald 2005; Dragovich and Morris 2002). Sediment transport occurs via both inter-rill areas (unconcentrated runoff pathways) and rills (concentrated runoff pathways) at the hillslope scale (Rose 2004).

The purpose of this chapter is to investigate the effects of prescribed burning and fire severity on surface runoff and erosion at the plot-scale (3 m^2). A number of hypotheses are addressed in relation infiltration, surface runoff and erosion:

Infiltration	**Runoff**	**Erosion**
Prescribed burning reduces infiltration (Hypothesis B)	Prescribed burning increases runoff (Hypothesis C)	Prescribed burning increases erosion (Hypothesis D)
Decreases in infiltration capacities following prescribed burning are related to the fire severity (Hypothesis B1)	Increases in runoff rates following prescribed burning are related to the fire severity (Hypothesis C1)	Increases in erosion rates following prescribed burning are related to the fire severity (Hypothesis D1)
Infiltration capacities recover fully within 18-months of prescribed burning (Hypothesis B2)	Runoff rates recover fully within 18-months of prescribed burning (Hypothesis C2)	Erosion rates recover fully within 18-months of prescribed burning (Hypothesis D2)

Measurements were conducted using rainfall simulations at Upper Yarra. Rainfall simulations are commonly used in post-fire studies (e.g. Cerdà and Doerr 2005; Cerdà and Doerr 2008; Cerdà *et al.* 1995; Doerr *et al.* 2003; Fernández *et al.* 2008; Kinner and Moody 2008, 2010; Malvar *et al.* 2011; Pierson *et al.* 2002; Robichaud 2000; Sheridan *et al.* 2007). They have several advantages over other methods (Table 18) including control of rainfall conditions, which enables more direct comparisons between different burn treatments. The rainfall conditions typically represent extreme events occurring infrequently at the site. Runoff and erosion responses to intense rainfall events are important to understand as they typically contribute disproportionately large amounts of sediment to streams and are particularly important from a water quality perspective (Smith *et al.* 2011c). However, such rainfall events are difficult to capture in studies which rely on natural rainfall, due to their rare occurrence. Another feature of rainfall simulations (or of any plot-scale study) is that hydrologic properties are averaged over the entire plot area. This is an advantage as it reduces the amount of variability within a fire severity treatment, making it easier to identify differences between treatments (i.e. between unburnt, low severity and high severity plots).

An important disadvantage of rainfall simulations, however, is that they are resource-intensive, requiring several people to perform a simulation, specialised skills and equipment. For example, in this study each 30 minute simulation involved several hours of preparation and therefore only a maximum of two simulations could be performed each day; this greatly limited the number of replicates that could be achieved. Another important limitation is that there are restrictions on where the plot can be located (discussed further in the methods section). Additionally, the parameters estimated from the simulations are only relative to the rainfall intensity used during the simulation. For example, the measured infiltration rate may be less than the infiltration capacity if the rainfall intensity does not exceed the infiltration capacity. [4] While these disadvantages need to be borne in mind, the advantages of using rainfall simulations outweighed the disadvantages for this study.

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[4] As mentioned in Chapter 5, the infiltration capacity is the maximum volume of water that can enter a unit area of the soil surface per unit time for a given hydraulic head. It is distinct from the infiltration rate, which is the actual rate of water uptake for a given rainfall intensity.

Table 18: Advantages and disadvantages of rainfall simulations

Advantages	Disadvantages
Able to compare different burn treatments under the same rainfall conditions.	Output parameters are limited to the rainfall intensity (e.g. measures the *apparent* infiltration rate for a given rainfall intensity, which may be less than the infiltration capacity).
Simulates runoff and erosion processes under intense rainfall conditions, which are difficult to capture under natural rainfall conditions.	Unable to capture the complexities of natural rainfall events during a simulation (e.g. during natural rainfall the rainfall intensity varies throughout a storm whereas during a simulation it remains constant; as discussed by Dunkerley (2008)).
Hydrologic properties and processes are averaged over the plot, reducing within-treatment variability and making it easier to detect differences between burn treatments.	Labour-intensive and time-consuming, and therefore difficult to achieve many replicates.
	Specialist equipment and expertise are needed.
	Access to a water source is needed and simulator must be positioned downslope of a road, therefore there are a limited number of locations where a simulation can be performed and the sites are not random.
	Aggregated plot outputs for runoff and sediment are measured rather than within-plot redistribution.
	Supply of eroded material and flow-paths are restricted by plot boundaries.

6.2 Methods

Rainfall simulations were conducted at the Upper Yarra site in early June 2009 and March 2010. Two simulations were conducted for each burn treatment (i.e. unburnt, low severity and high severity) except in March 2010 when there were no high severity simulations due to wet weather restricting site access, mechanical problems and other projects needing the simulator at the same time.

The simulation plots were located adjacent to the treatment plots described in Chapter 3. A number of criteria were used to select suitable locations for the plots:

- cover of litter and ash similar to that observed more broadly within the fire severity treatment
- no cross-slope, which could cause concentrated flow along plot edges
- all plots with similar slope gradients
- no large surface depressions or holes which could have a large effect on runoff rates
- no trees or large shrubs obstructing the installation of the simulator
- short distances between plots (if possible) to reduce equipment transport time
- plots downslope and within 50 m of road for water pumping.

The 3 m^2 plots (1.5 m x 2 m) were bordered by steel sheets, hammered into the ground and sealed to the soil surface with petroleum jelly. At the downslope end of the plots, stainless steel troughs were used to collect overland flow (Figure 39). The percent cover of ash, vegetation, rock fragments and bare soil were visually estimated for each plot prior to the simulation (Table 19).

(a) Simulation plot

(b) Rainfall simulator set-up

(c) Calibrating the rainfall simulator

(d) Collecting runoff samples

Figure 39: Photographs to illustrate using the rainfall simulator.

Table 19: Characteristics of each rainfall simulation plot

Timing	Fire severity	Plot No.	Slope	Cover estimates (%)				Depth of litter/ash (mm)[B]
				Ash	Vegetation[A]	Rock	Bare soil	
Autumn 2009	Unburnt	1	25°	0	95	0	0	22 (25)
		2	23°	0	60	0	40	25 (17)
	Low	3	26°	100	0	0	0	16 (9)
		4	24°	70	5	0	25	15 (8)
	High	5	23°	70	10	30	0	15 (7)
		6	23°	60	10	40	0	18 (9)
Autumn 2010	Unburnt	6	23°	0	95	0	5	21 (13)
		7	25°	0	85	0	15	16 (9)
	Low	9	25°	40	30	0	30	30 (7)
		10	24°	30	20	0	50	29 (16)

[A] Includes scorched leaves fallen from the canopy after the fire; [B] Mean values reported with standard deviations in brackets (n = 20)

The rainfall simulator (see Sheridan *et al.* 2007 for a full description) delivered raindrops from three oscillating fan-shaped sprays sweeping intermittently across the plot surface. The rainfall energy was 295 kJ ha^{-1} mm^{-1}. A 1000 L tank supplied the water, which was collected from a nearby stream (McMahons Creek). Rainfall was applied at two intensities: 100 mm h^{-1} (for 30 minutes) and 60 mm h^{-1} (until a steady-state runoff rate was reached). The 100 mm h^{-1} intensity is similar to the intensities used in several other post-fire studies (e.g. Benavides-Solorio and MacDonald 2001; Leighton-Boyce *et al.* 2007; Pierson *et al.* 2002; Robichaud 2000; Sheridan *et al.* 2007); with an average recurrence interval (ARI) of approximately 100 years at Upper Yarra (i.e. for a 100 mm h^{-1} intensity over 30 minutes) (Bureau of Meteorology 2009), it represents an extreme event. The 60 mm h^{-1} storm was chosen to represent the effects of burning and fire severity on runoff and erosion during lower intensity storms; it was the lowest intensity achievable with the simulator. A 60 mm h^{-1} intensity for 30 minutes is still an extreme event at Upper Yarra, with an ARI of approximately 50 years (Bureau of Meteorology 2009). Prior to commencing a simulation, the simulator was calibrated with a plastic sheet covering the plot. The rainfall intensity of the simulator was adjusted until the volume of runoff was equivalent to a runoff ratio of 100% for the desired rainfall intensity.

During the simulation timed runoff samples were collected at regular intervals in 500 ml plastic bottles to measure the runoff rate and sediment concentration. Typically 12 samples were collected – eight during the 100 mm h^{-1} simulation (at one to five minute intervals) and four during the 60 mm h^{-1} simulation (consecutively under steady-state conditions). The samples were used to generate a time-series of runoff and erosion during the 100 mm h^{-1} simulation, while during the 60 mm h^{-1} simulation they were used to capture the steady-state conditions. In the laboratory the wet samples were weighed, and then oven-dried and reweighed (to three decimal places) to determine the volume of water and the sediment concentration. After each simulation the leaf litter and ash were collected along two transects (10 cm x 2 m) within each plot to determine gravimetrically their water storage capacity. The depth of litter or ash was also measured at 10 cm intervals along the transects. Gravimetric soil moisture contents were measured before and after the simulations. Bulk soil samples from 10 locations and two depths (0-2 cm and 2-5 cm) were collected from outside the plots prior to the simulation and within the plots following the simulation. Mean flow velocities were approximated during the simulations by adding dye to the runoff at designated points within the plots and recording the time required for the dye to travel specific distances.

The runoff samples collected during the rainfall simulations were used to calculate runoff rates, runoff ratios, infiltration rates and sediment concentrations (Table 20). Statistical analyses were generally not performed due to the small sample sizes (n = 2 for each treatment), with the exception of basic linear and non-linear regressions to explore the relationships between surface cover (percent bare soil / ash), runoff ratios and sediment concentration. Data from all burn treatments and time-steps were pooled for this analysis, which was done using Statistica 6.0.

Table 20: Equations used to calculate key parameters from rainfall simulation data

Parameter	Equation	Definition of terms
R: runoff rate (mm h^{-1})	$R = \frac{V/A}{T}$	V = volume of runoff in a sample (mm^3) A = plot area (mm^2) T = time required to collect sample (m)
RR: runoff ratio (%)	$RR = \frac{R}{P} \times 100$	R = runoff rate (mm h^{-1}) P = rainfall rate (mm h^{-1})
I: infiltration rate (mm h^{-1})	$I = P - R$	R = runoff rate (mm h^{-1}) P = rainfall rate (mm h^{-1})
C: sediment concentration (g L^{-1})	$C = \frac{S}{V}$	S = dry weight of sediment in sample (g) V = volume of runoff in sample (L)

In addition to the rainfall simulations, this chapter also presents surface cover measurements. Photographs were taken of the soil surface at each infiltrometer sampling point at the following times (see Chapter 3 for more details about the spatial arrangement and number of sample points): autumn 2009 (pre- and post-burn), spring 2009, autumn 2010 and spring 2010. The size of the photographs were adjusted so they all showed the same 0.5 x 0.5 m area Then the percent cover of surface vegetation (including leaf litter, bark, logs, low shrubs and grass) was visually estimated for each photograph. The mean cover values for each fire severity at each measurement date were used to predict runoff and erosion rates beyond 12-months using the regression equations described above.

6.3 Results

6.3.1 Infiltration

Steady-state infiltration rates were low. For example, the overall mean was 9.4 mm h^{-1} in June 2009 for the 100 mm h^{-1} simulations (Table 21 and Figure 40). For the 100 mm h^{-1} simulations in June 2009, burnt steady-state infiltration rates were approximately 20% of unburnt rates (means of 4 mm h^{-1} and 3.6 mm h^{-1} for burnt plots compared with 21 mm h^{-1} for unburnt plots) while differences between the severities were small (a mean difference of 0.4 mm h^{-1} for the 100 mm h^{-1} simulations). In March 2010 there was some evidence of post-fire recovery. Burnt steady-state infiltration rates were approximately 50% of unburnt rates. Results were generally similar for the 60 mm h^{-1} and 100 mm h^{-1} simulations in June 2009, while in March 2010 they were higher for the 100 mm h^{-1} simulations.

6.3.2 **Runoff**

Steady-state runoff ratios were very high. For example, the overall mean was 90% in autumn 2009 for the 100 mm h^{-1} simulations (Table 21 and Figure 41). They were approximately 15-20% greater for burnt compared with unburnt plots in 2009 (for the 100 mm h^{-1} simulations) and there was little evidence of recovery in 2010. In contrast, differences between the severities were small. For example, there was only a 3% difference between the severities in June 2009 for the 100 mm h^{-1} simulations. There was a larger difference in runoff rates between burnt and unburnt plots for the 60 mm h^{-1} simulation compared with the 100 mm h^{-1} simulation in June 2009. Conversely, in March 2010 the 100 mm h^{-1} simulation resulted in the larger difference.

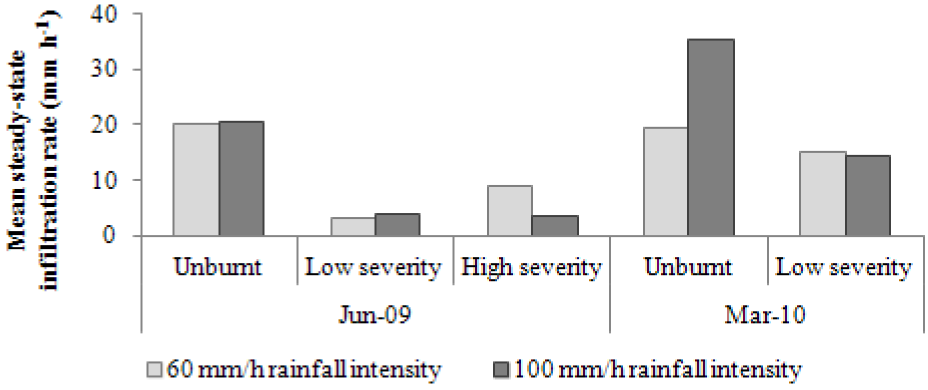
6.3.3 **Erosion**

For the 100 mm h^{-1}simulations in June 2009, burnt steady-state sediment concentrations were almost an order of magnitude greater than unburnt ones (means of 4.4 g L^{-1} and 3.8 g L^{-1} for burnt plots versus 0.5 g L^{-1} for unburnt plots) (Table 21 and Figure 40). Burnt peak sediment concentrations were approximately 4-6 times greater than unburnt ones (means of 16 g L^{-1} and 11 g L^{-1} for burnt plots versus 3 g L^{-1} for unburnt plots). In contrast, differences between the severities were smaller. For example, low severity steady-state sediment concentrations were 1.2 times greater than high severity ones, and low severity peak sediment concentrations were 1.5 times greater than high severity ones in June 2009. Steady-state sediment concentrations showed little evidence of recovery. There was approximately one order of magnitude difference between burnt and unburnt treatments for both the 2009 and 2010 simulations. However, differences in peak sediment concentrations between burnt and unburnt plots were slightly less in 2010 than in 2009, with burnt peak sediment concentrations approximately three times greater than unburnt ones in 2010, compared with approximately 4-6 times greater in 2009 (Figure 40 and Figure 41). Sediment concentrations during the 100 mm h^{-1} simulations were approximately twice those during the 60 mm h^{-1} simulations for the burnt plots, while there was little difference for the unburnt plots.

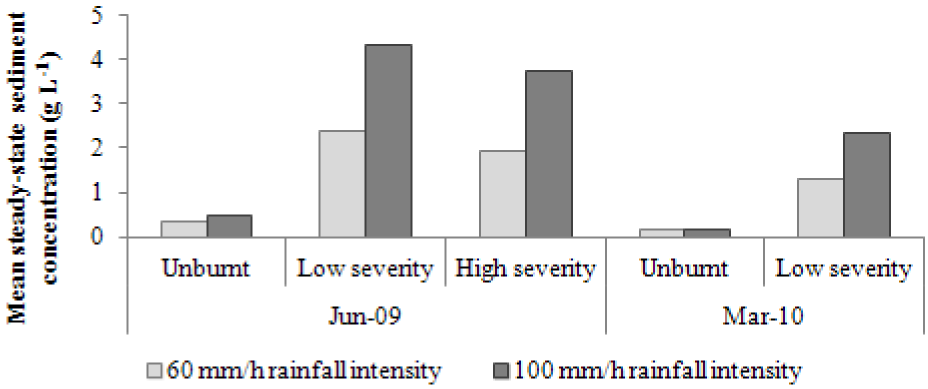
Table 21: Statistics for unburnt, low severity and high severity rainfall simulations at Upper Yarra. Results are reported for each plot per treatment.

		June 2009						**March 2010**			
	Rainfall (mm h^{-1})	**Unburnt**		**Low severity**		**High severity**		**Unburnt**		**Low severity**	
		Plot 1	**Plot 2**	**Plot 3**	**Plot 4**	**Plot 5**	**Plot 6**	**Plot 7**	**Plot 8**	**Plot 9**	**Plot 10**
Steady-state runoff rate (*R*) (mm h^{-1})	60	48	32	56	58	51	51	39	42	-	45
	100	85	74	97	94	96	97	62	67	75	90
Steady-state runoff ratio (*RR*) (%)	60	81	54	97	97	86	85	66	70	-	75
	100	85	74	94	95	96	97	62	67	81	90
Steady-state infiltration rate (*I*) (mm h^{-1})	60	11.6	28	3.8	2.1	8.6	8.9	21	18	-	10.2
	100	14.9	26	3	5.1	3.7	3.4	38	33	19.4	15.1
Steady-state sediment concentration (*C*) (g L^{-1})	60	0.1	0.6	3.4	1.4	2.1	1.8	0.1	0.2	-	1.3
	100	0.2	0.8	6.2	2.5	3.9	3.6	0.2	0.1	2.4	2.3
Peak sediment concentration (g L^{-1})	100	2.4	3.4	21.0	10.5	11.3	10.2	0.8	1.9	4.5	5.0
Approximate flow velocity (m s^{-1})	100	0.03	0.02	0.05	0.07	0.05	0.04	0.01	0.01	0.01	0.01
Water storage capacity of litter / ash (mm)	n/a	2.0	1.9	1.8	1.2	1.3	1.2	2.1	2.1	4.0	2.1
Time to runoff (s)	100	90	90	78	110	90	130	140	100	100	160

(a) Steady-state infiltration rate



(b) Steady-state sediment concentration



(c) Peak sediment concentration

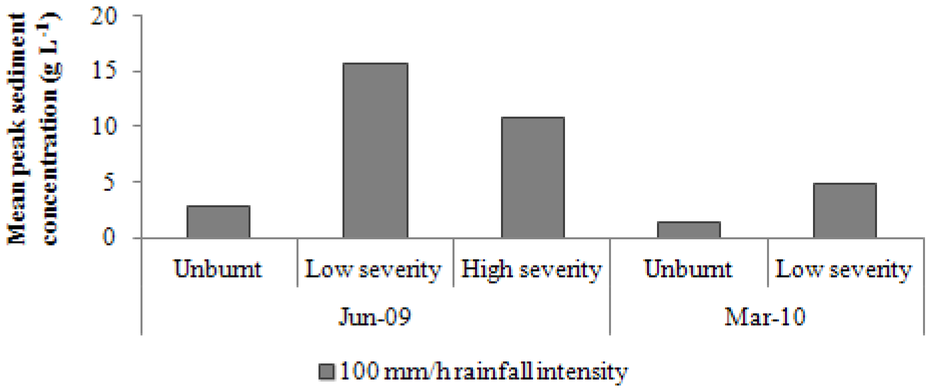


Figure 40: Mean values (n=2) for (a) steady-state infiltration rate; (b) steady-state sediment concentration; and (c) peak sediment concentration during the 60 mm h^{-1} and 100 mm h^{-1} rainfall simulations for unburnt, low severity and high severity plots.

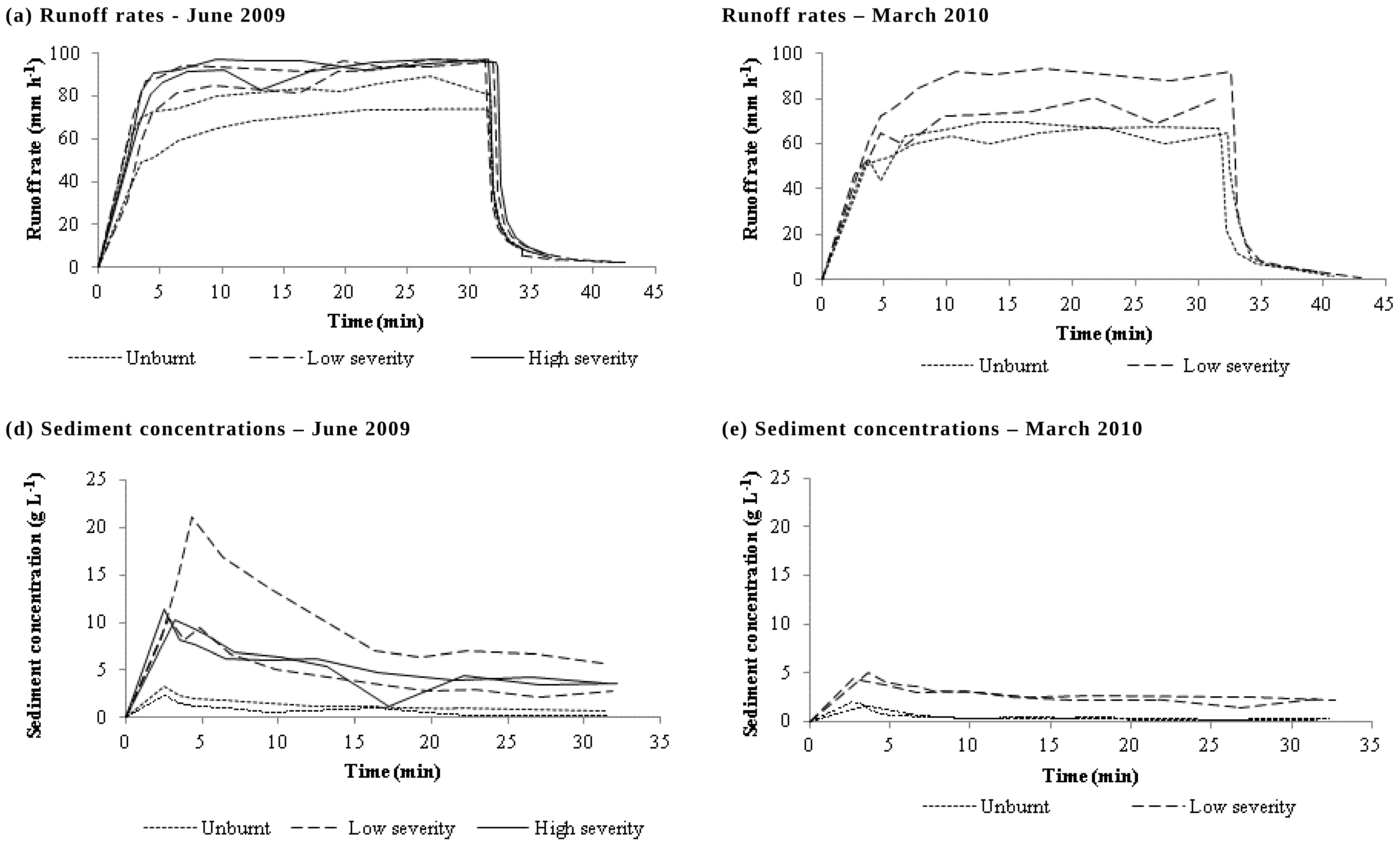


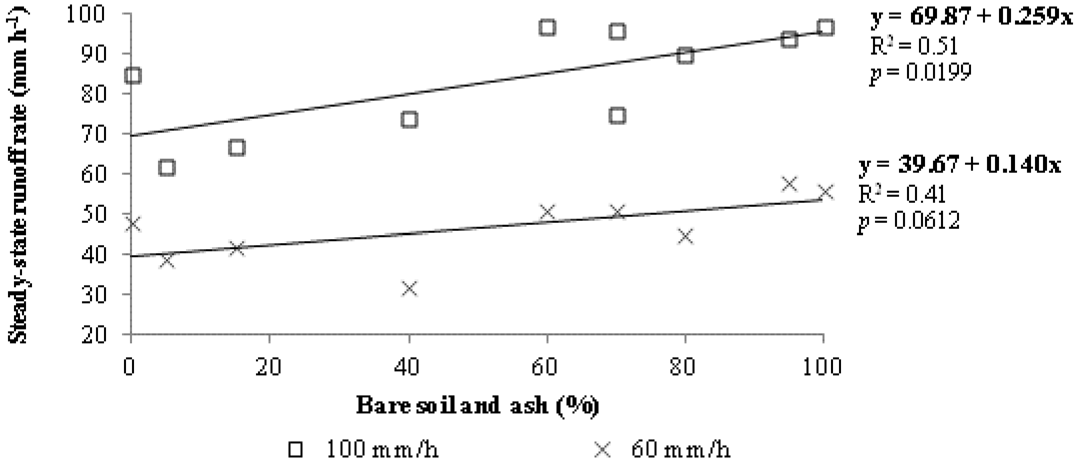
Figure 41: Time-series charts of runoff rate and sediment concentration during the 100 mm h^{-1} rainfall simulations in autumn 2009 and autumn 2010 for unburnt, low severity and high severity plots.

6.3.4 **Effects of surface vegetative cover**

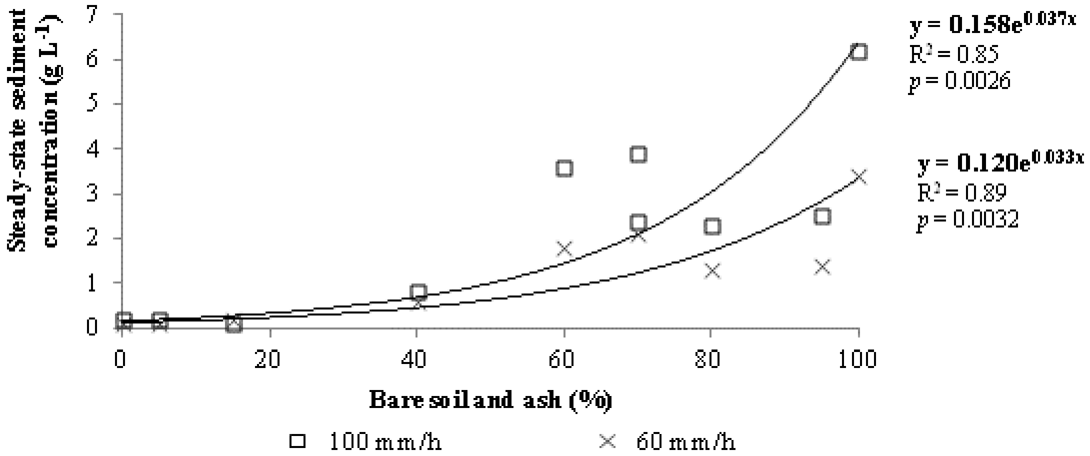
As mentioned previously, surface vegetation cover is thought to affect runoff and erosion by increasing the surface storage capacity, slowing overland flow velocities and protecting the soil surface from rain drop impact. At Upper Yarra, the burnt (ash covered) plots had slightly lower surface storage capacities compared to the unburnt (vegetated) plots. The mean storage capacities were 2 mm, 1.5 m and 1.3 mm for the unburnt, low severity and high severity plots, respectively in June 2009 (Table 21). This difference in storage capacity did not appear to affect the time to start of runoff (Table 21) or the length of the recession curves at the end of the simulations (Figure 41). The approximate flow velocities were slightly higher for the burnt plots compared with the unburnt plots in June 2009. The mean flow velocities were 0.3 m s^{-1}, 0.5 m s^{-1} and 0.6 m s^{-1} for the unburnt, low severity and high severity plots, respectively (Table 21).

There were significant linear relationships between the percent cover of bare soil / ash and the steady-state runoff rate with the runoff rate increasing slightly with an increase in the percentage of bare soil / ash for both the 60 mm h^{-1} and 100 mm h^{-1} simulations (Figure 42a). In contrast, relationships between the percent cover of bare soil / ash and the erosion rate (peak and steady-state) were exponential, with substantial increases in erosion when the percentage of bare soil / ash exceeded approximately 60% (Figure 42b and Figure 42c).

(a) Steady-state runoff rate



(b) Steady-state sediment concentration



(c) Peak sediment concentration

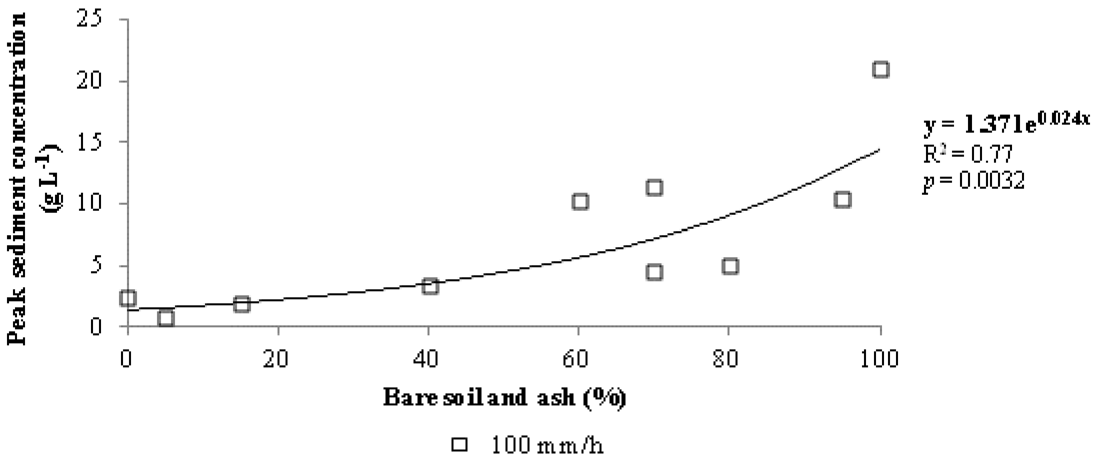


Figure 42: Relationships between bare soil / ash cover (%) and the (a) steady-state runoff rate, (b) steady-state sediment concentration, and (c) peak sediment concentration during rainfall simulations at Upper Yarra. Results from all burn treatments (unburnt, low severity and high severity) and both measurement dates (June 2009 and March 2010) are combined in this analysis.

6.3.5 **Predictions of post-fire recovery over 18 months**

Figure 43 shows the mean amount of vegetative cover on the soil surface as a function of time since the burn at Upper Yarra (see Appendix 15 for the same data at Big Ben and Mt Cole). Immediately post-burn, surface vegetation cover was 18% and 0% in the low and high severity areas, respectively; this increased to 35% and 42% by 6-months, 38% and 36% by 12-months, and 54% and 47% by 18-months after burning. These vegetative cover values and the regression equations between bare soil / ash, runoff and erosion shown in Figure 42, were used to predict the recovery of runoff and erosion at the plot-scale over 18-months (assuming that changes in vegetation cover is a major driver of post-fire recovery). The predictions show that while runoff rates and sediment concentrations decline over 18-months post-burn, full recovery is unlikely to occur over this time (Figure 44).

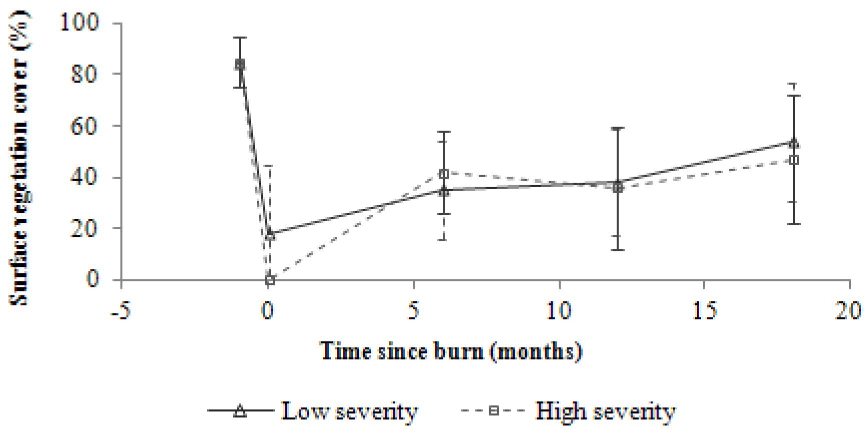


Figure 43: Mean values for surface vegetative cover as a function of time since fire for low and high severity areas at Upper Yarra. Error bars denote the standard deviations.

(a) Predicted steady-state runoff rates **(b) Predicted steady-state sediment concentrations** **(c) Predicted peak sediment concentrations**

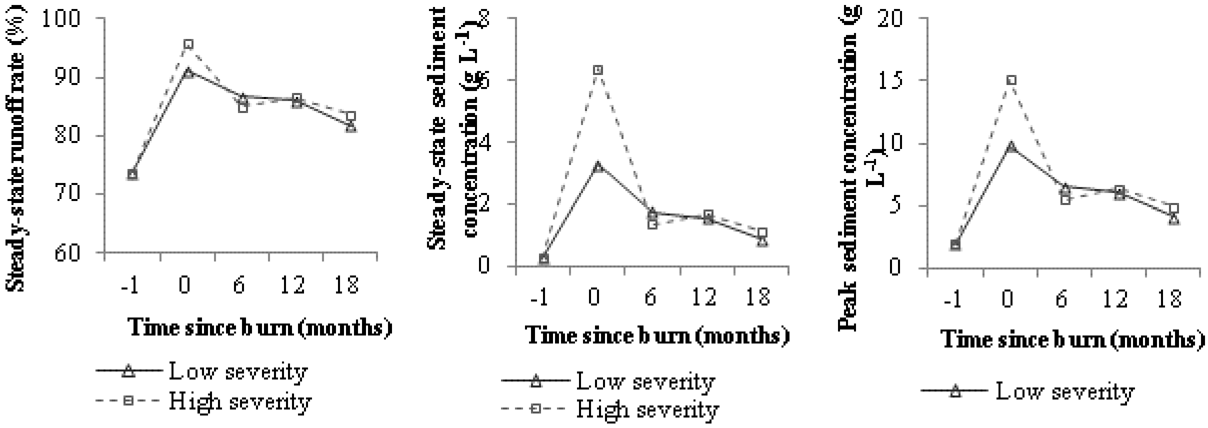


Figure 44: Predicted post-fire recovery of (a) steady-state runoff rates, (b) steady-state sediment concentrations, and (c) peak sediment concentrations with recovering surface vegetative cover at the plot-scale. Calculations are based on the functions presented in Figure 42 for the 100 mm h^{-1} rainfall simulations and the vegetative cover data in Figure 43.

6.4 Discussion

This chapter has quantified the effects of low and high fire severity prescribed burns on infiltration, runoff and erosion at the plot-scale under simulated rainfall conditions. Several hypotheses have been addressed and the outcomes in relation to those hypotheses are described in Table 22.

Table 22: A summary of the results in relation to each hypothesis

Hypothesis	Outcome	Rationale
Infiltration:		
Prescribed burning reduces infiltration (Hypothesis B)	Accepted	During the 100 mm h^{-1} simulations the burnt steady-state infiltration rates were approximately 20% of unburnt rates in June 2009.
Decreases in infiltration capacities following prescribed burning are related to the fire severity (Hypothesis B1)	Rejected	Differences in the steady-state infiltration rates for low and high severity plots were relatively small. For example, there was a mean difference between the severities of 0.4 mm h^{-1} for the 100 mm h^{-1} simulations in June 2009.
Infiltration capacities recover fully within 18-months of prescribed burning (Hypothesis B2)	Rejected	The burnt steady-state infiltration rates were approximately 50% of the unburnt rates 11-months after burning. Extrapolations of the data suggest that infiltration rates are unlikely to recover fully within 18-months.
Surface runoff:		
Prescribed burning increases runoff (Hypothesis C)	Accepted	During the 100 mm h^{-1} simulations burnt steady-state runoff ratios were 15-20% greater than unburnt ratios in June 2009 and March 2010.
Increases in runoff rates following prescribed burning are related to the fire severity (Hypothesis C1)	Rejected	Differences in runoff between the low and high severity plots were relatively small. For example, in June 2009 runoff ratios differed by 3% between the low and high severity plots.
Runoff rates recover fully within 18-months of prescribed burning (Hypothesis C2)	Rejected	Differences between the burnt and unburnt steady-state runoff ratios were similar six-weeks and 11-months post-burn. Extrapolations of the data suggest that infiltration rates are unlikely to recover fully within 18-months.
Surface erosion:		
Prescribed burning increases erosion (Hypothesis D)	Accepted	Burnt steady-state sediment concentrations were almost an order of magnitude higher than unburnt concentrations in both June 2009 and March 2010.
Increases in erosion rates following prescribed burning are related to the fire severity (Hypothesis D1)	Rejected	Differences in steady-state sediment concentrations between the low and high severity plots were relatively small. For example, low severity steady-state sediment concentrations were approximately 1.2 times greater than high severity ones in June 2009.
Erosion rates recover fully within 18-months of prescribed burning (Hypothesis D2)	Rejected	Steady-state sediment concentrations in burnt plots showed little evidence of recovery from 2009 to 2010, but peak sediment concentrations were slightly less in 2010. Extrapolations of the data suggest that infiltration rates are unlikely to recover fully within 18-months.

6.4.1 **Infiltration, runoff and erosion in unburnt areas**

Steady-state infiltration rates were low and runoff ratios high in the unburnt plots at Upper Yarra (e.g. 20 mm h^{-1} in June 2009 during the 100 mm h^{-1} simulation; Figure 40). In contrast, infiltration rates reported for unburnt areas in other rainfall simulation studies using similar rainfall intensities (i.e. 60-100 mm h^{-1}) were higher (Table 23). For example, 75 mm h^{-1} for wet eucalypt forest in Victoria, Australia (Sheridan *et al.* 2007), 72 mm h^{-1} (repellent) to 102 mm h^{-1} (non-repellent) for eucalypt plantation in Portugal (Leighton-Boyce *et al.* 2007), 60 mm h^{-1} for mixed heathland in Spain (Fernández *et al.* 2008) and 36-62 mm h^{-1} for coniferous forest in the Rocky Mountains, USA (Robichaud 2000). The infiltration rates reported for these studies were often overall rates (not steady-state rates), which is likely to have contributed to the higher values. Other factors such as high water repellency (Chapter 4) are also likely to have contributed to the very low rates at Upper Yarra. In March 2010, when water repellency was less (Chapter 4), the mean steady-state infiltration rate was higher (36 mm h^{-1} for the 100 mm h^{-1} simulations).

Sediment concentrations from the unburnt plots during the simulations were low with the mean steady-state concentration being 0.5 g L^{-1} and the mean peak concentration being 2.9 g L^{-1} for the 100 mm h^{-1} simulations in June 2009 (Figure 40). These values are comparable to those measured in other simulation studies for unburnt forests (Table 23). For example, 0.9 g L^{-1} for wet eucalypt forest in Victoria, Australia (Sheridan *et al.* 2007), 0.3-0.4 g L^{-1} for eucalypt plantation in Portugal (Leighton-Boyce *et al.* 2007) and 1.9 g L^{-1} for ponderosa pine in the Colorado Front Range, USA (Benavides-Solorio and MacDonald 2001).

Table 23: A summary of results from selected post-fire rainfall simulation studies. Reported values are for the duration of the simulation unless otherwise stated.

	Location	Method	Time since burn	Treatment	Mean values for multiple simulations: Runoff ratio (%)	Infiltration rate (mm h^{-1})	Sediment concentration (g L^{-1})	Author
Mediterranean Europe	North-central Portugal – eucalypt plantation	80-85 mm h^{-1} 60 min 0.25 m^2 plots	3-24 months (6 campaigns)	Moderate severity wildfire; unploughed	55	44	0.35	Malvar *et al.* (2011)
				Moderate severity wildfire; ploughed	38	30.4	0.14	
	Galicia, Spain – mixed heathland	67 mm h^{-1} 30 min 1 m^2 plots	Several days	Unburnt	10	60.4	297	Fernández *et al.* (2008)
				Low severity prescribed burn	42	39.7	1771	
	Valencia province, Spain – Aleppo pine (*Pinus Halepensis*)	55 mm h^{-1} 60 min 1 m^2 plots	3-10 days	Wildfire burnt ash and needle covered ground	1.75	54.0	1.16	Cerdà and Doerr (2008)
				Wildfire burnt ash only covered ground	2.38	53.7	1.93	
				Wildfire burnt bare ground	43.28	31.2	11.63	
	North-central Portugal – eucalypt plantation	~100 mm h^{-1} 30-min 0.36 m^2 plots	10-years (long unburnt)	Litter removed	99.7 (repellent) 13.2 (non-repellent)[A]	6 (repellent) 94 (non-repellent)[A]	2.3 (repellent) 1.6 (non-repellent)[A]	Leighton-Boyce *et al.* (2007)
				Litter retained	33.1 (repellent) 2.1 (non-repellent)[A]	72 (repellent) 102 (non-repellent)[A]	0.4 (repellent) 0.3 (non-repellent)[A]	
			5 months	Wildfire burnt	69.9 (repellent) 0 (non-repellent)[A]	36 (repellent) 104(non-repellent)[A]	0.9 (repellent) 0 (non-repellent)[A]	
	Valencia province, Spain – scrubland	55 mm h^{-1} 60 min 1 m^2 plots	0.5 years	High severity wildfire	45 (steady-state)	25 (steady-state)	Not reported	Cerdà (1998)
			1.5 years		28 (steady-state)	37 (steady-state)		
			2.5 years		14 (steady-state)	46 (steady-state)		
			5.5 years		6% (steady-state)	52 (steady-state)		
	Valencia province, Spain – scrubland	55 mm h^{-1} 60 min 1 m^2 plots	10 years	Wildfire burnt; north aspect; 85-90% vegetation cover	11	> 45 (steady-state)	0.56	Cerdà *et al.* (1995)
			10 years	Wildfire burnt; south aspect; 60-65% vegetation cover	38	39 (steady-state)	0.90[1]	
			2 years	Wildfire burnt; north aspect; 25-30% vegetation cover	41	28 (steady-state)	7.62	

	Location	Method	Time since burn	Treatment	Mean values for multiple simulations			Author
					Runoff ratio (%)	Infiltration rate (mm h^{-1})	Sediment concentration (g L^{-1})	
North America	Idaho, USA – sagebrush steppe	85 mm h^{-1} 60 min 0.5 m^2	0 months [B]	Unburnt (coppice / interspace)	39 / 63	42 / 26 (steady-state)	0.5 / 4.0	Pierson *et al.* (2009)
				Burnt (coppice / interspace)	76 / 55	21 / 33 (steady-state)	3.0 / 16.2	
		85 mm h^{-1} 60 min 0.5 m^2		Unburnt	4	62 (steady-state)	3	
				Burnt	27	47 (steady-state)	62.6	
	Colorado Front Range, USA – Ponderosa pine[C]	80 mm h^{-1} 30 min	1-2 months	Low severity wildfire & unburnt	55	30-32	1.9 g L^{-1}	Benavides-Solorio and MacDonald (2001)
				Moderate severity wildfire	58	29	4 g L^{-1}	
				High severity wildfire	66	20	23.5 g L^{-1}	
	Northern Rocky Mountains, USA – coniferous forest[D]	94 mm h^{-1} 30 min	Several days	Unburnt	34 (steady-state)	36-62 (steady-state)	Not reported	Robichaud (2000)
				Low severity prescribed burn	47 (steady-state)	10-63 (steady-state)		
				High severity prescribed burn	43 (non-repellent; steady-state) 55 (repellent; steady-state)	22-74 (non-repellent; steady-state) 15-40 (repellent; steady-state)		
Australia	Victoria, Australia – wet eucalypt forest	100 mm h^{-1} 30 min 3 m^2	1-2 months	Unburnt	26	75	0.9	Sheridan *et al.* (2007)
				High severity wildfire	35	65	13.3	
	Victoria, Australia - dry eucalypt forest and pine plantation	100 mm h^{-1} 30 min 3 m^2	14 months	Wildfire burnt; eucalypt forest	82	16	1.8	Smith *et al.*(2011b)
				Wildfire burnt; pine plantation harvested after the fire	76	22	2.2	

[A] Water repellency removed using a surfactant in the water; [B]There were also measurements done 1 year post-burn; [C]The results reported here are only for the Bobcat fire; [D]The results reported here are only for the Hermada burn

6.4.2 **Effects of burning on infiltration, runoff and erosion**

Burnt steady-state infiltration rates were approximately 20% of those in unburnt areas in June 2009 (for the 100 mm h^{-1} rainfall intensity) (Table 21), while correspondingly the runoff ratios were 15-20% higher for the burnt plots. Other rainfall simulation studies have also reported lower infiltration rates in burnt compared with unburnt plots. For example burnt infiltration rates were approximately 87% of the unburnt rate in wet eucalypt forest in Victoria, Australia (Sheridan *et al.* 2007), 50% of the unburnt rate (under repellent conditions) in a eucalypt plantation in Portugal (Leighton-Boyce *et al.* 2007), 67% of the unburnt rate in mixed heathland in Spain (Fernández *et al.* 2008) and as little as 24% of the unburnt rate in coniferous forest in the Rocky Mountains, USA (Robichaud 2000) (Table 23). The relatively small difference in runoff ratios relative to the much larger difference in infiltration rates probably reflects the very high rainfall intensities used during the simulations. This is illustrated in Chapter 8 (Section 8.3.2). As the infiltration rate reached (or neared) its maximum potential, any additional rainfall became runoff, reducing the apparent differences in runoff between burnt and unburnt plots.

Steady-state sediment concentrations were approximately an order of magnitude higher in the burnt compared with unburnt plots for both rainfall intensities in 2009 while peak sediment concentrations were approximately 4-6 times greater in the burnt plots (Figure 40). Similar magnitude increases in erosion following burning have been reported in other rainfall simulation studies. For example, a 6-fold increase in heathland in Spain (Fernández *et al.* 2008), a 12-fold increase (from unburnt / low severity to high severity) in ponderosa pine forest in the USA (Benavides-Solorio and MacDonald 2001) and a 15-fold increase in wet eucalypt forest in Australia (Sheridan *et al.* 2007).

Higher infiltration and erosion rates in burnt areas are often attributed to increased soil water repellency (Robichaud 2000) and the loss of vegetative cover (Benavides-Solorio and MacDonald 2001). At Upper Yarra, the burnt areas had both stronger repellency (Chapter 4) and less vegetative cover (Figure 43). The relative effect of these factors on infiltration, runoff and erosion during the rainfall simulations is difficult to determine from the data. However, given that fire-induced changes to water repellency had little effect on infiltration capacities at the point-scale (Chapter 5), it is possible that the loss of vegetative cover was the major driver of lower infiltration and higher runoff during the rainfall simulations. This was demonstrated in regression analyses where the percent bare soil/ash was found to be positively correlated with the runoff ratio. These regressions also show strong positive relationships between percent bare soil/ash and the sediment concentration (Figure 42).

As outlined in the conceptual model presented in Chapter 3, vegetation cover reduces runoff rates by protecting the soil surface, thus preventing soil sealing and rain-splash erosion (DeBano *et al.* 1998; Larsen *et al.* 2009; Neary *et al.* 1999; Sayer 2006). The rainfall simulations showed that surface interception rates were slightly higher in unburnt compared with burnt areas at Upper Yarra (the storage capacity of unburnt litter was 2 mm versus 1.4 mm for ash; Table 21). The lack of vegetative cover in the burnt plots may have led to reduced infiltration and increased runoff by causing soil sealing and/or enhancing the effects of soil water repellency. In eucalypt plantations in Portugal, Leighton-Boyce *et al.* (2007) reported that water repellency had a larger impact on infiltration when there was no surface litter (Figure 45). They attributed the higher infiltration rates beneath the litter to reduced raindrop impact and rainfall storage in the litter. Another potential explanation for higher infiltration rates in the unburnt plots (despite the strong water repellency) could be the depth of ponded water. Ponded depths can be greater in areas with surface vegetation as the higher surface roughness results in reduced flow velocities (Stoof *et al.* 2012). Infiltration capacities in water repellent soils are highly sensitive to slight differences in the depth of ponded water (Letey 2001). As illustrated in Figure 46, more pores become available for infiltration as the ponded depth increases due to the greater hydraulic head of the water. This could be an important determinant of differences in infiltration capacities between burnt and unburnt plots at Upper Yarra, where the soils were highly repellent and there were only small differences in surface storage capacities between the burnt and unburnt plots.

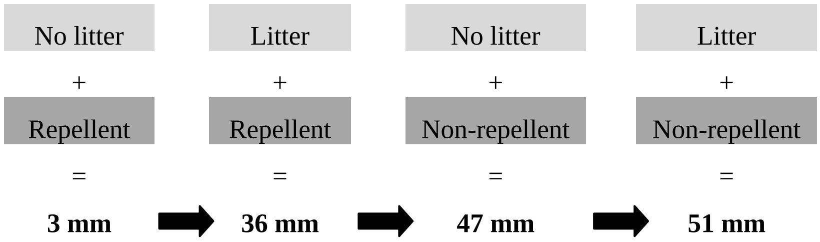


Figure 45: Summary of results from Leighton-Boyce *et al.* (2007) showing the relative contribution of leaf litter and soil water repellency to total infiltration in long unburnt plots. The total infiltration is for a 100 mm h^{-1} simulated rainfall event lasting 30 minutes.

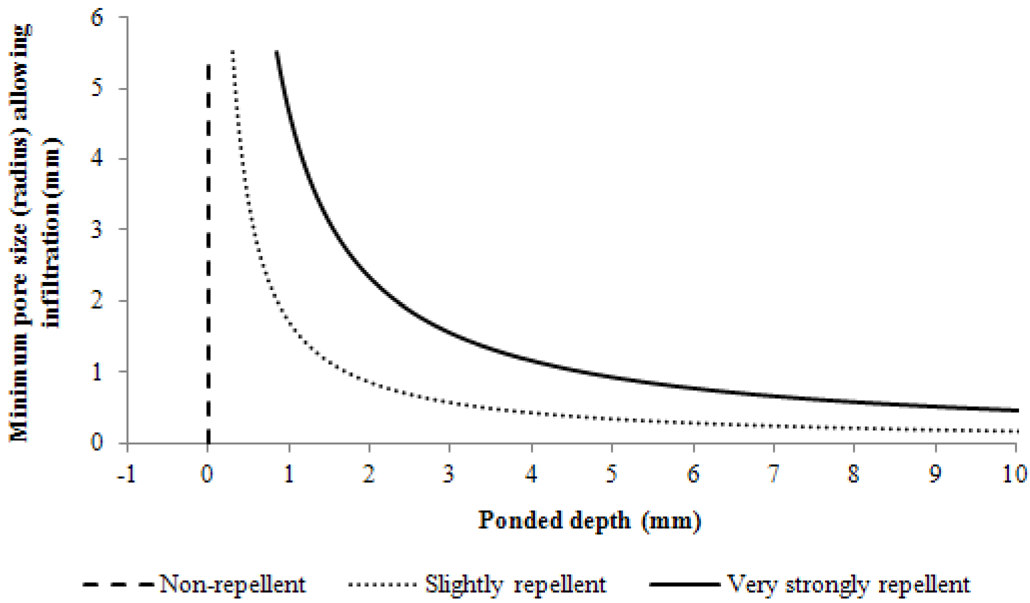


Figure 46: The effect of ponded depth on the minimum pore size able to infiltrate for very strongly water repellent (34 mN m^{-1}), slightly water repellent (56 mN m^{-1}) and non-repellent (72 mN m^{-1}) soils. The chart is based on equations from Letey (2001). As ponded depth increases, smaller pores allow infiltration because of the greater hydraulic head.

The loss of vegetation cover in burnt plots is also likely to have triggered higher erosion rates. As outlined in the conceptual model (Chapter 3), surface vegetation protects the soil surface from raindrops and thus limits or prevents rain-splash erosion; it also reduces flow velocities, thus reducing the ability of overland flow to detach and transport sediment (DeBano *et al.* 1998; Larsen *et al.* 2009; Neary *et al.* 1999; Sayer 2006). During the rainfall simulations, there was widespread interrill erosion and slightly faster flow velocities in burnt plots relative to unburnt plots. Water repellency may also have contributed to the higher erosion rates in the burnt plots, where there was no vegetation to protect the soil surface. Leighton-Boyce *et al.* (2007) found that water repellency had substantial effects on erosion rates when there was no vegetation cover, but little effect when some was present.

6.4.3 **Effects of fire severity on infiltration, runoff and erosion**

Differences in infiltration, runoff and erosion between the fire severities were small (mean infiltration rates differed by only 0.4 mm h^{-1}, mean runoff ratios differed by only 3% and mean steady-state sediment concentrations differed by only 0.6 g L^{-1} during the 100 mm h^{-1} simulations). These results reflect similarities between the fire severities in terms of soil water repellency (Chapter 4) and surface cover (Table 19). Other studies report larger differences in infiltration, runoff and erosion between fire severities (Table 23). For example, Benavides-Solorio and MacDonald (2001) measured infiltration rates of 30-32 mm h^{-1} and sediment concentrations 1.9 g L^{-1} in unburnt / low severity plots versus 20 mm h^{-1} and 23.5 g L^{-1} in high severity plots. Robichaud (2000) measured a 10-40% difference in infiltration rates between low and high severity plots (before water repellency was overcome in the high severity plots).

6.4.4 **Post-fire recovery**

Infiltration rates and runoff ratios continued to differ between burnt and unburnt plots 11-months post-burn (Figure 40) and a full recovery of runoff ratios was not predicted to occur within 18-months (Figure 44). Other studies have reported periods of post-fire recovery for infiltration and runoff of many years, so the results reported here are not unusual. For example, Cerdà and Doerr (2005) found that post-fire runoff ratios fully recovered within seven years for shrubs, herbs and dwarf shrubs, but for trees (*Pinus halepensis*) the runoff ratios still continued to decline after 11 years. Cerdà (1998) found that infiltration rates following fire (in scrubland) increased for the duration of his study (5.5 years), with the largest increases occurring in association with rapid vegetation regeneration in the first two years.

Steady-state sediment concentrations also showed little evidence of recovery between the 2009 and 2010 rainfall simulations and extrapolations from the data (Figure 44) suggested that erosion rates were unlikely to fully recover within 18-months. Benavides-Solorio and MacDonald (2001) found that high severity plots burnt six-years previously had sediment yields that were twice those of unburnt plots but only 6.6% that of recently burnt high severity plots. Conversely, Sheridan *et al.* (2007) found that erosion rates in high severity plots, which increased 10-fold immediately following the fire, had decreased to pre-fire levels within two years. In both instances the plots had been exposed to natural rainfall in addition to the simulated rainfall.

6.5 Conclusion

Prescribed burning resulted in lower steady-state infiltration rates (burnt rates approximately 20% of unburnt rates), higher steady-state runoff ratios (burnt ratios approximately 15-20% greater than unburnt ratios) and higher steady-state sediment concentrations (burnt concentrations approximately an order of magnitude greater than unburnt concentrations) at the plot-scale. In comparison, differences in infiltration rates, runoff ratios and sediment concentrations between the low and high severity plots were small. Almost one year after burning there were still large differences between the burnt and unburnt plots in terms of infiltration, runoff and erosion despite infiltration rates and peak sediment concentrations declining somewhat relative to unburnt plots. Predictions based on rates of vegetation recovery suggest that full recovery is unlikely to be achieved within 18-months of burning.

7. Effects of prescribed burning on hillslope-scale runoff and erosion

This chapter quantifies the effects of fire severity and burn patchiness at the hillslope-scale using 116 unbounded runoff samplers (opening 10 cm wide; ~ 100 m from catchment divide) installed below six hillslope treatments: (1) high fire severity (crown scorched), (2) low fire severity (crown intact; understorey scorched), (3) unburnt, and low fire severity above (4) 1 m, (5) 5 m, and (6) 10 m wide unburnt patches.

7.1 Introduction

This chapter quantifies the effect of prescribed burning on surface runoff and erosion at the hillslope-scale. As discussed in Chapter 2, surface runoff and erosion at the hillslope-scale are likely to be affected not only by the fire severity (e.g. Neary *et al.* 1999; Shakesby and Doerr 2006), but also by the spatial arrangement of different fire severity patches (Benavides-Solorio and MacDonald 2005; Kutiel *et al.* 1995). Prescribed burns are often patchy (Penman *et al.* 2007) and several authors have acknowledged the potential significance of this to runoff and erosion connectivity (e.g. Benavides-Solorio and MacDonald 2005; Kutiel *et al.* 1995; Smith *et al.* 2010), yet there is little research about its effects (with the exception of Moody *et al.* 2008; Robichaud and Monroe 1997). In contrast, there are numerous studies about the effects of patchiness on runoff and erosion in patchily vegetated environments – for example tropical savannas and semi-arid shrublands (Bartley *et al.* 2006; Boer and Puigdefábregas 2005; Cerdà 1997; Ludwig *et al.* 2007; Mayor *et al.* 2009; Reaney 2003; Reid *et al.* 1999. Those studies report that the proximity of bare patches to a hillslope outlet {Bartley, 2006 #55) and patch density (Bautista *et al.* 2007; Boer and Puigdefábregas 2005) are important factors influencing the connectivity of runoff and erosion (discussed in Chapter 2). This study focuses on the effects of unburnt patches downslope of a burnt hillslope; this patch arrangement is likely to occur frequently in prescribed burnt landscapes. A number of hypotheses are addressed:

Runoff	**Erosion**	**Hillslope connectivity**
Prescribed burning increase runoff (Hypothesis C)	Prescribed burning increases erosion (Hypothesis D)	Connectivity of surface runoff and erosion following prescribed burning depends on the size and arrangement of fire severity and unburnt patches (Hypothesis E).
Increases in runoff rates following prescribed burning are related to the fire severity (Hypothesis C1)	Increases in erosion rates following prescribed burning are related to the fire severity (Hypothesis D1)	
Runoff rates recover fully within 18-months of prescribed burning (Hypothesis C2)	Erosion rates recover fully within 18-months of prescribed burning (Hypothesis D2)	

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 that the plot openings were unusually narrow (10 cm). Runoff plots measure runoff and erosion in response to individual storms and seasonal changes and thus provide insight into runoff and erosion processes under a range of conditions. However, long monitoring periods may be required to capture a desired range of rainfall conditions. A key feature of unbounded plots is that flow paths are uninterrupted by plot boundaries. It may be reasonable to assume that the runoff and sediment collected in the samplers are representative of volumes / loads occurring anywhere on the hillslope (except close to the catchment divide); this is because flowpaths in forests are often short (e.g. Bren and Turner 1979; Sheridan *et al.* 2007).

In contrast, bounded plots tend to interrupt convergent and divergent flow paths and the movement of sediment along plot margins resulting in different volumes / loads than if the plot was unbounded (Brazier 2004). Furthermore, erosion rates may be underestimated if the sediment supply within a bounded plot is exhausted because there is no replenishment from upslope of the plot (Boix-Fayos *et al.* 2006). These drawbacks of bounded plots mean that the measurements are less likely to be representative of hillslope-scale processes, and it is more difficult to scale-up the results. An advantage of bounded plots is that the plot boundaries enable a more direct comparison of treatments as the drainage area is defined exactly (Boix-Fayos *et al.* 2006). However, for the purposes of this study, that advantage of bounded plots does not outweigh the disadvantages, and hence unbounded plots were used.

The narrow plot openings of the runoff samplers used in this study made 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.

7.2 Methods

7.2.1 Field measurements

Unbounded runoff samplers were used to measure surface runoff and erosion at Upper Yarra from August 2009 (four months post-burn) to December 2010 (20 months post-burn). Figure 47 illustrates the design of the samplers which consisted of box-guttering (10 cm 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 in April 2010 following several events where the 17 L buckets overflowed. The samplers were installed in transects on planar hillslopes (near Blocks 1, 3 and 4 – see Chapter 3) downslope of six treatments: (1) high fire severity, (2) low fire severity, (3) unburnt, low fire severity above (4) 1 m, (5) 5 m and (6) 10 m wide unburnt patches (Figure 48, Figure 49 and Figure 50). There were 20 samplers in each transect except for the 1 m unburnt patch treatment, which had 16 samplers. This transect was established opportunistically with spare materials, but there were insufficient materials to construct 20 samplers. Although the transects themselves were not randomly located (their locations were chosen to be representative of the conditions implied by the treatment), the samplers were randomly spaced along the transects. Distances between the samplers ranged from 0.1 m to 2 m. The transects were 80-100 m from the catchment divide on hillslopes with slopes of 24-28^{o} (see Figure 49 for exact slope lengths and gradients).

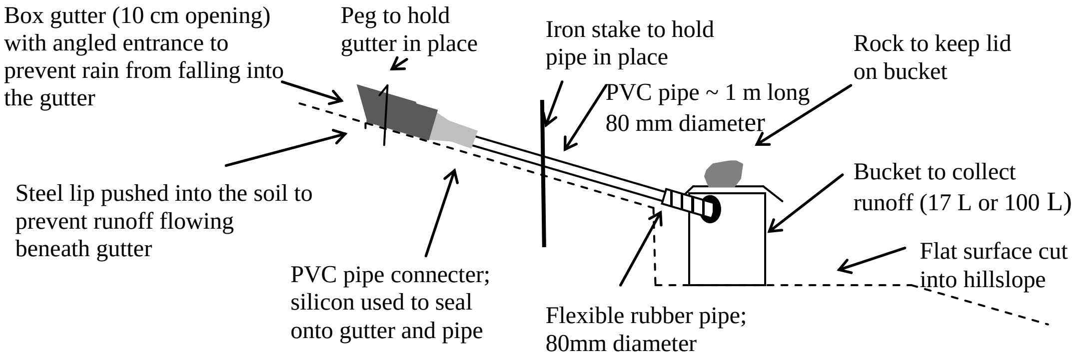


Figure 47: Design of the runoff samplers. Surface runoff and sediment were measured regularly following rainfall using these samplers.

Figure 48: A transect of 20 runoff samplers on the high severity hillslope in August 2009. Samplers were located approximately 100 m from the ridge on planar hillslopes. The total hillslope length was approximately 200-300 m.

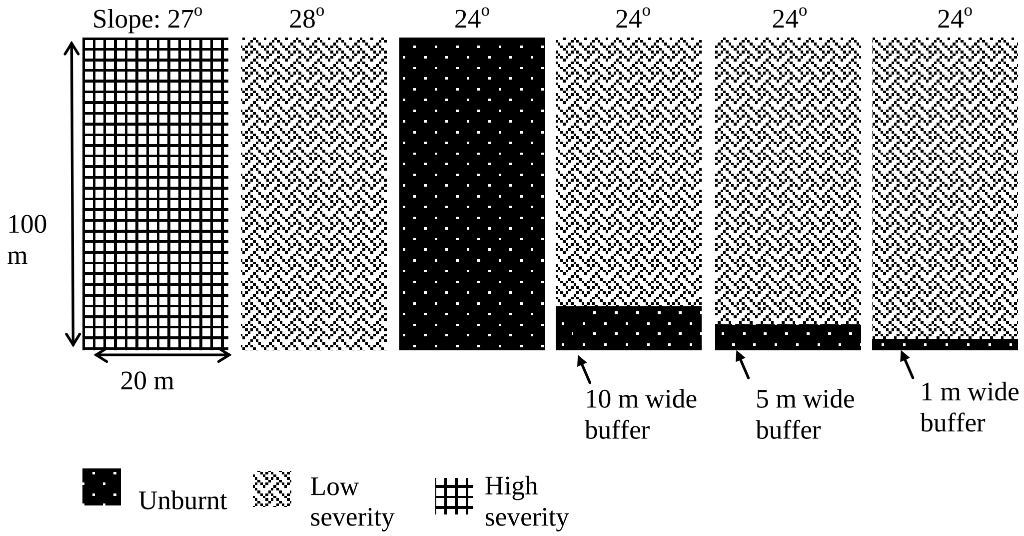


Figure 49: Patch arrangements above the runoff samplers. The low severity, 10 m buffered, 5 m buffered and unburnt transects were located side-by-side on the same hillslope. Average slopes for each hillslope are shown above the diagram.

Unburnt **Low severity** **High severity**

Figure 50: Photographs to illustrate the appearance of the fire severities above the runoff samplers.

On 29 occasions the runoff volume was measured in the samplers by either:

- measuring the runoff depth and converting that to a volume using a calibrated depth-volume conversion chart, or
- measuring the volume directly using a measuring cylinder for volumes < 0.25 L (when the depth in the bucket was too shallow to measure).

Evaporation from the buckets was not an issue because the buckets had lids, sealing the contents within. It is assumed that very little evaporation would have occurred via the PVC piping.

Sediment concentrations were measured in up to 10 runoff samplers per transect on 24 occasions (some rainfall events were not sampled due to insufficient rain or time to collect the samples). Often there were only a few samplers that were eligible for sediment analysis; the following criteria were applied:

- sampler must contain > 0.25 L of runoff.[5]
- sampler must not have overflowed.[6]

If > 10 samplers met the above criteria, then 10 samplers were randomly selected for analysis. Conversely, if < 10 samplers met the above criteria then sediment was analysed in all the eligible samplers. After thorough stirring, either a 0.5 L sample was collected from the bucket or the entire contents of the bucket were collected (when the total volume was < 0.5 L). The sediment concentration was determined gravimetrically (to four decimal places) in the laboratory by weighing, drying (at 100 ^{o}C until all the moisture had evaporated) and then reweighing the sample.

An automatic weather station measured rainfall, temperature, relative humidity and solar radiation at three minute intervals. The weather station was located in a clearing within 2.5 km of the runoff samplers and at a similar elevation to the samplers.

7.2.2 **Event parameters**

A number of event-based parameters were calculated from the data (Table 24). Runoff volumes from individual samplers (v_i) were converted to runoff volumes per metre width of hillslope (V) for a

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[5] Samples < 0.25 L were considered too small to provide a representative measure of sediment concentration as the sediment concentration could have been easily influenced by individual sediment particles.

[6] An implication of this criterion was that average sediment concentrations for a transect may have been underestimated for larger rainfall events. The overflowing samplers, with the largest runoff volumes, are likely to have caused the greatest amount of erosion and thus had the highest sediment concentrations.

transect and measurement date by summing the individual volumes for each functioning sampler[7] and then dividing the total by the product of the number of functioning samplers along that transect on that measurement date (*n*) and the width of each sampler (i.e. 0.1 m). Assuming the connected length for runoff was < 100 m, this value represented the average amount of runoff reaching any point on the hillslope (except points on the upper slopes where the connected length was truncated by the hillslope divide). If there were overflowing buckets, then the overall runoff volume (*V*) was extrapolated from a linear regression equation for runoff volume (*V*) against percentile runoff volume (*x*) for rainfall events that had no overflowing samplers (Table 25). The percentile used depended on the maximum number of buckets that had overflowed on a particular measurement date. An assumption of this approach was that the relationship between the overall runoff volume (*V*) and percentile runoff volume (x) was the same for rainfall events of different magnitude.

The sediment concentrations from individual samplers (c_i) were used to calculate the average sediment concentration of the runoff (*C*) for a transect and measurement date by summing the individual concentrations and then dividing by the number of samplers that were analysed along that transect on that measurement date (*b*) (Table 24). These values were multiplied by the overall runoff volume (*V*) to estimate the sediment load per metre width of hillslope (*S*) (Table 24).[8]

For hillslopes with unburnt patches downslope of a low severity burn, the reduction in runoff volume below the unburnt patch (*VR*) was calculated by dividing the runoff volume from downslope of the unburnt patch (*VP*) by the runoff volume on the low severity hillslope (*VL*) and then subtracting that value from one. Percent reductions in sediment load (*LR*) were calculated in the same way using sediment load rather than runoff volume data. These calculations are based on the assumption that the amount of runoff and sediment generated upslope of the unburnt patches was comparable to the amounts generated on the low severity hillslope. This assumption is feasible since the low severity

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[7] Clearly the sample size was smaller for instances where some samplers were not functioning. This may have reduced the statistical confidence of the estimate.

[8] By excluding overflowing tanks from the sediment concentration measurements, average sediment concentrations (*C*) and sediment loads per metre width of hillslope (*S*) are likely to have been underestimated on the burnt hillslopes (where the overflowing tanks most commonly occurred). Therefore, the data provide a conservative estimate of the relative difference in runoff and erosion between burnt and unburnt hillslopes.

hillslope and the burnt areas on the patchy hillslopes were similar in appearance and in close proximity of eachother.

Table 24: Equations used to calculate parameters from the runoff sampler data for each measurement date.

Event parameter	Equation	Definition of inputs
V: Runoff volume per metre width of hillslope (L m^{-1})	$V = \frac{\sum_{i=1}^{i=n} v_i}{n \times 0.1}$	v_i: runoff volume in individual sampler *i* (L) *n:* number of functioning samplers along that transect on that measurement date
Median v: median runoff volume in the individual samplers for a given transect and measurement date (L)	$Median\ v = \frac{v_{max} - v_{min}}{2}$	v_{max}: maximum runoff volume in an individual sampler (L). For overflowing tanks the maximum was assumed to be 40 L. v_{min}: minimum runoff volume in an individual sampler (L)
R: Runoff ratio (%)	$R = \frac{V}{P} \times 100$	*V*: runoff volume per metre width of hillslope (L m^{-1}) *P*: total upslope rainfall volume per metre width of hillslope (L m^{-1})
C: Sediment concentration in runoff (g L^{-1})	$C = \frac{\sum_{i=1}^{i=b} c_i}{b}$	c_i: sediment concentration in sampler *i* (g L^{-1}) *b*: number of samplers analysed along the transect on the measurement date
S: Sediment load per metre width of hillslope (g m^{-1})	$S = V \times C$	*V*: runoff volume per metre width of hillslope (L m^{-1}) *C*: sediment concentration of runoff (g L^{-1})
VR: reduction in runoff volume below an unburnt patch (%)	$VR = (1 - \frac{VP}{VL}) \times 100$	*VP*: runoff volume (L m^{-1}) collected downslope of an unburnt patch *VL*: runoff volume (L m^{-1}) collected on the low severity hillslope
LR: reduction in sediment load below an unburnt patch (%)	$LR = (1 - \frac{LP}{LL}) \times 100$	*LP*: sediment load (g m^{-1}) collected downslope of an unburnt patch *LL*: sediment load (g m^{-1}) collected on the low severity hillslope

Table 25: Regression equations used to calculate the runoff volume per metre width of hillslope (*V*) for rainfall events when there were overflowing samplers (and hence the equation in Table 24 could not be used). *V* = the runoff volume per metre width of hillslope (L m^{-1}); x is a given percentile runoff volume per metre width of hillslope (L m^{-1}). Equations were derived using data from measurement dates when there were no overflowing samplers.

Treatment	Regression equation	x	R^2
High severity	$V = 23.304x + 5.4279$	60th percentile	0.7561
Low severity	$V = 44.832x + 8.1642$	40th percentile	0.8235
1 m buffer	$V = 42.442x + 0.8621$	60th percentile	0.8157
5 m buffer	$V = 17.167x + 0.7692$	80th percentile	0.7337
10 m buffer	$V = 13.45x + 0.7868$	80th percentile	0.8744
Unburnt	Not required – no overflowing tanks		

7.2.3 Overall parameters for the 16-month period

Overall parameters for the entire measurement period (16-months) were calculated for runoff volume (*VO*), runoff ratio (*RO*), sediment load (*SO*), runoff reduction (*VRO*) and sediment reduction (*SRO*) to enable broad comparisons across multiple rainfall events. Table 26 summarises the equations used to calculate those overall parameters. Sometimes the cumulative runoff volumes and sediment loads were converted to annual statistics so that comparisons could be made between studies. This was done by dividing the cumulative value by 16 and then multiplying by 12.

Table 26: Equations used to calculate overall runoff and erosion parameters for the 16-month measurement period.

Overall parameters	**Equation**	**Definition of terms**
VO: cumulative runoff volume for 16-months (L m^{-1})	$VO = \sum_{j=1}^{j=m} V_j$	V_j = runoff volume per metre width of hillslope (L m^{-1}) for measurement date *j* *m:* number of measurement dates
RO: average runoff ratio for 16-months (%)	$RO = \frac{\sum_{j=1}^{j=m} R_j}{m}$	R_j = runoff ratio (%) for measurement date *j* *m* = number of measurement dates
SO: cumulative sediment load for 16-months (g m^{-1})	$SO = \sum_{j=1}^{j=m} L_j$	S_j = sediment load (g m^{-1}) for measurement date *j* *m* = number of measurement dates
VRO: total reduction in runoff volume for 16-months (%)	$VRO = \frac{\sum_{j=1}^{j=m} VR_j}{m}$	VR_j = reduction in runoff (%) for measurement date *j* *m* = number of measurement dates
SRO: total reduction in sediment load for 16-months (%)	$LRO = \frac{\sum_{j=1}^{j=m} LR_j}{m}$	LR_j = reduction in sediment load (%) for measurement date *j* *m* = number of measurement dates

7.2.4 **Data analysis**

In addition to presenting the raw parameters defined in Table 24 and Table 26, several statistical analyses were performed including:

- **Significance testing between treatments for each measurement date.** For each measurement date, median runoff volumes (*median v*) and the mean sediment concentration of runoff (*C*) for each transect were compared using Mann Whitney tests and t-tests, respectively. Median values were calculated for runoff (rather than mean values) to reduce the bias caused by the overflowing samplers. Each of the overflowing samplers were assigned a value of 40 L in the analysis because this was the mean volume measured in the 100 L samplers for rainfall events when a 17 L sampler would have overflowed. The sediment concentration data were approximately normally distributed, and hence means and t-tests were appropriate.
- **Significance testing between seasons.** The data were grouped into seasons (winter/spring 2009; summer/autumn 2009-10; winter/spring 2010) and mean seasonal values were calculated for the runoff ratio (*R*) and sediment concentration (*C*). T-tests were used to determine the statistical significance of differences between these seasonal means.
- **Double mass curves.** Double mass curves were calculated using runoff volume (*V*) and sediment concentration (*C*) for each measurement date to detect relative changes over time in runoff and erosion rates between pairs of treatments. T-tests were used to determine the statistical significance of these relative changes.
- **Regression analysis.** The association between sediment load and rainfall intensity was explored using regression analysis (in Sigma Plot 2001). The sediment load for each measurement date was plotted against the rainfall intensity. For this analysis, different measures of intensity were trialled (e.g. I_3, I_{10}, I_{30} and I_{120}).
- **Function fitting.** A function was determined to describe the relationship between the width of the unburnt patch and its sediment trapping efficiency (in Sigma Plot 2001). Separate curves were fitted for rainfall events where the average recurrence interval (ARIs) = 10 years (i.e. 27th

November 2009) and the ARI ≤ 1 year (i.e. all other events) to illustrate the effect of rainfall intensity on the effectiveness of the unburnt patches in reducing runoff and sediment connectivity. A hypothetical curve was also plotted for an extreme rainfall event.

A basic assumption of several of the analyses described above was that the hillslopes were the same except for differences between the burn treatments. This assumption was supported by the data presented in Chapter 3, which showed that the hillslopes were similar in terms of aspect, soil type, slope and vegetation type.

7.3 Results

7.3.1 Rainfall during the measurement period

Monthly rainfall totals were often above the long-term average, especially from August to December 2010 (Figure 17 in Chapter 3). The 30 minute maximum rainfall intensities (I_{30}) for each measurement date usually had an average recurrence interval (ARI) of < 1 year (Table 27) (Bureau of Meteorology 2009). An exception was the 27th November 2009 when the I_{30} was 44.4 mm h^{-1} and the ARI was 10 years. There were two large rainfall events contributing to this measurement date: 25.6 mm over approximately 19 hours on the 22nd November and 25.4 mm over approximately 2 hours on the 26th November (Figure 51).

Table 27: Rainfall properties for each measurement date. The shading illustrates the magnitude of each event relative to the other events for each rainfall property. The average recurrence intervals (ARIs) are shown for each rainfall event based on the 30 minute maximum rainfall intensity.

Date	Total	I_3 mm h^{-1}	I_{30} mm h^{-1}	I_{300} mm h^{-1}	ARI for I_{30}
28-Aug-09	55.2	16	5.6	2	<1
02-Sep-09	17.2	12	4.8	1	<1
07-Sep-09	4.8	16	4.8	0.5	<1
10-Sep-09	42.2	8	3.2	2	<1
16-Sep-09	3.8	4	1.6	0.5	<1
18-Sep-09	16.2	8	5.2	2	<1
22-Sep-09	8	12	6.8	2	<1
25-Sep-09	10.6	8	4.8	1	<1
30-Sep-09	96.4	16	5.6	3	<1
13-Oct-09	21.6	20	5.2	1	<1
20-Oct-09	49.8	16	4.4	2	<1
27-Nov-09	62	80	44.4	5	10
01-Dec-09	14.6	24	6	1	<1
12-Dec-09	40	24	9.2	3	<1
06-Jan-10	37.4	24	6.4	3	<1
25-Jan-10	41.4	28	7.2	3	<1
10-Feb-10	7.2	4	2.8	1	<1
16-Feb-10	15.6	28	10	2	<1
21-Mar-10	62	60	20.4	2	1
09-Apr-10	25.4	116	10.4	2	<1
29-Apr-10	61.6	28	9.2	3	<1
21-Jun-10	140	20	10.8	4	<1
12-Jul-10	38.2	12	5.2	2	<1
26-Jul-10	39.6	24	11.6	3	<1
02-Sep-10	200.6	20	10.4	3	<1
07-Sep-10	46.2	12	7.2	2	<1
19-Oct-10	120	24	6	3	<1
02-Nov-10	82.2	44	19.6	4	<1
10-Dec-10	157.4	64	18	5	<1

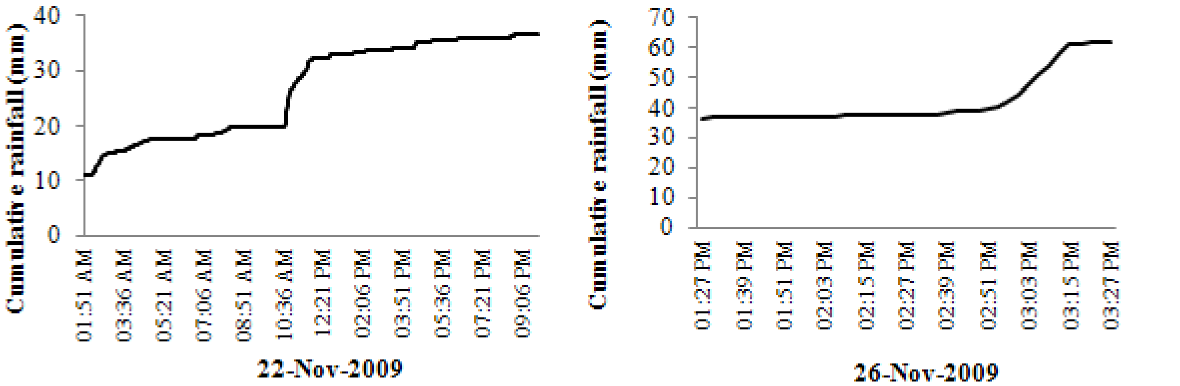


Figure 51: Cumulative rainfall for two major rainfall events contributing to the 27th November 2009 measurement date. The rainfall totals were 25.6 mm on the 22nd November and 25.4 mm on the 26th November. In addition to those events, there were other smaller rainfall events contributing to the totals measured on the 27th November 2009.

7.3.2 **Visual indicators of erosion in burnt areas**

Rain-splash and sheet wash erosion were evident at the Upper Yarra and Mt Cole on the burnt hillslopes as indicated by numerous soil pedestals (10- 30 mm in height) (Figure 52). There was no rill erosion at the Upper Yarra, while at Mt Cole there were some shallow rills in the ash layer soon after the burn (Figure 52). There was no evidence of erosion following the burn at Big Ben. Intense storms in 2010 at all sites resulted in eroded roads and incised gullies at Big Ben. However, erosion on the burnt hillslopes did not appear to worsen as a result of these storms.

(a) Soil pedestals **(b) Soil pedestals** **(c) Shallow rills in the ash**

Figure 52: Evidence of erosion at Mt Cole.

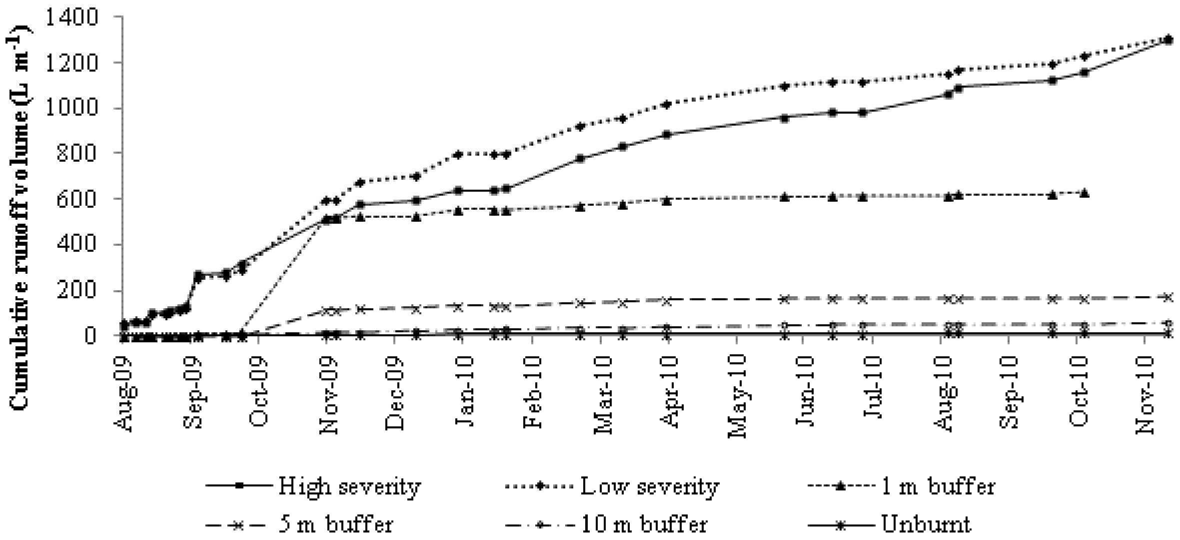
7.3.3 **Overall runoff volumes and sediment loads**

Cumulative runoff volumes (*VO*) for the 16-months were approximately two orders of magnitude larger on burnt hillslopes compared with unburnt hillslopes, while differences between the severities were much smaller (runoff volumes were 1307 L m^{-1} and 1300 L m^{-1} for the low and high severity hillslopes, respectively, compared with 15 L m^{-1} for the unburnt hillslope; Table 28). Similarly, differences in cumulative sediment loads (*SO*) for the 16-months were much larger between the burnt and unburnt hillslopes than between the severities with burnt cumulative sediment loads approximately three orders of magnitude larger than unburnt sediment loads (sediment loads were 1671 g m^{-1} and 2058 g m^{-1} for the low and high severity hillslopes, respectively, compared with 1.5 g m^{-1} for the unburnt hillslope). There were distinct differences in the cumulative runoff volumes and sediment loads between uniformly burnt hillslopes and those with unburnt patches. Total reductions in runoff volume were 48.5%, 86.7% and 95.4% for the 1 m, 5 m and 10 m patches, respectively (Table 28), and total reductions in sediment load were 1.5%, 96.6% and 99.8% for the 1 m, 5 m and 10 m patches, respectively. Much of the runoff and sediment were delivered from just a few intense storms (Figure 53). For example, for the 1 m unburnt patch hillslope,79% of the cumulative runoff volume and 99% of the cumulative sediment load were recorded on 27th November 2009.

Table 28: Overall runoff volumes and sediment loads for the 16-month measurement period

Hillslope treatment	**Cumulative runoff volume (*VO*) (L m^{-1})**	**Average runoff ratio (*RO*) (%)**	**Cumulative sediment load (*SO*) (g m^{-1})**	**Total reduction in runoff (*VRO*) (%)**	**Total reduction in sediment load (*SRO*) (%)**
Unburnt	15.0	0.01	1.5	n/a	n/a
Low severity	1307.2	0.86	1671.4	n/a	n/a
High severity	1300.3	0.86	2057.9	n/a	n/a
Low severity upslope of 1 m unburnt patch	634.6	0.47	1645.8	48.5	1.5
Low severity upslope of 5 m unburnt patch	174.5	0.12	56.8	86.7	96.6
Low severity upslope of 10 m unburnt patch	60.7	0.04	4.2	95.4	99.8

(a) Cumulative runoff volume from August 2009 to December 2010



(b) Cumulative sediment load from August 2009 to November 2010

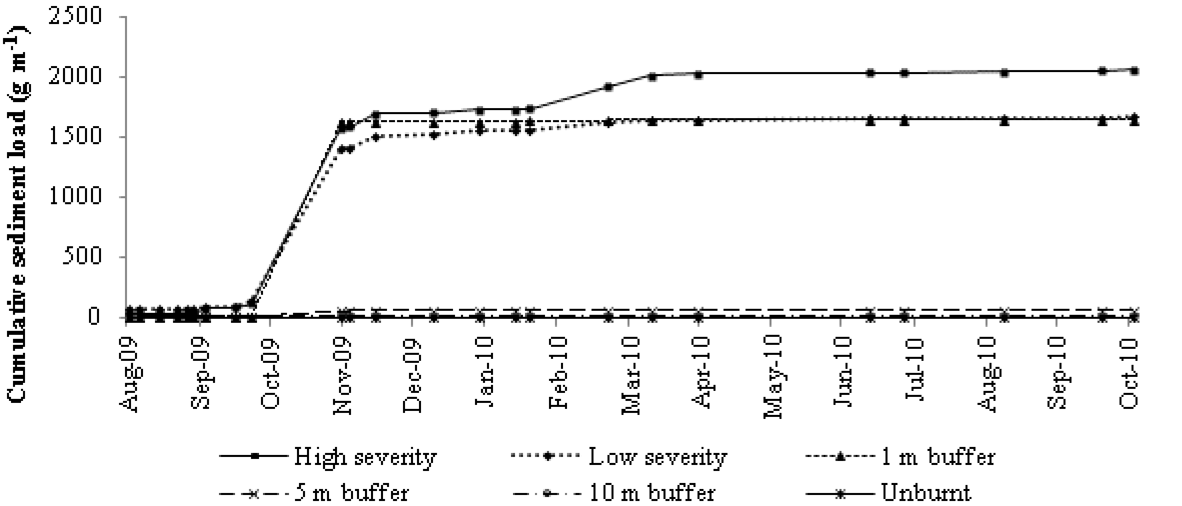
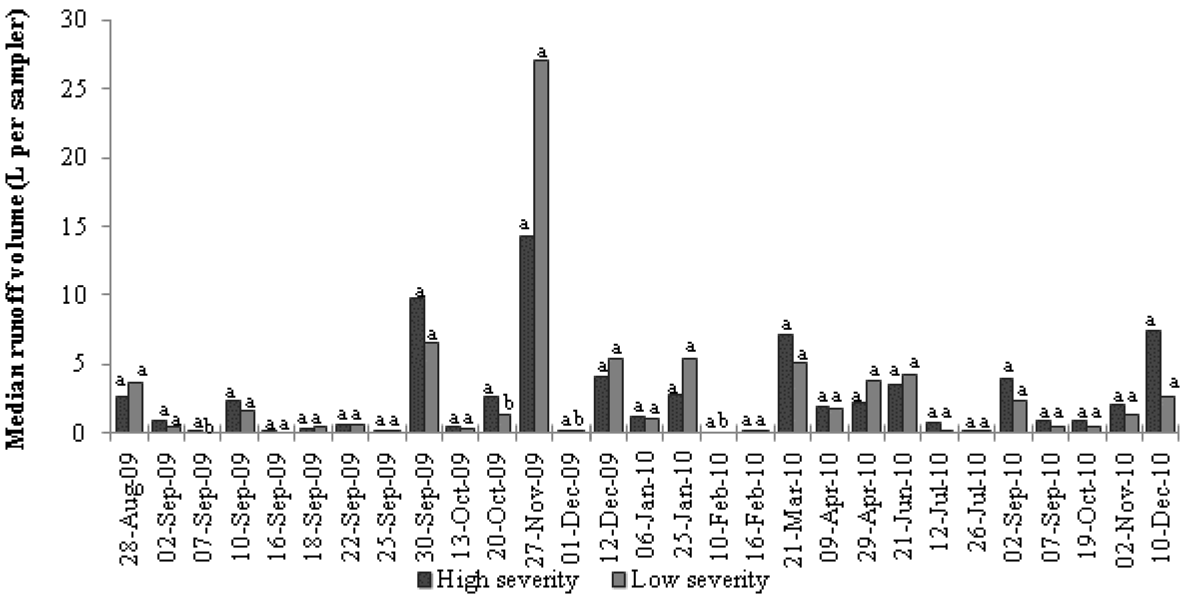


Figure 53: Cumulative (a) runoff volume and (b) sediment load for each hillslope treatment.

7.3.4 Differences between the low and high severity hillslopes

For most measurement dates there were no statistically significant differences in median runoff volume (*median v*) and mean sediment concentration (*c*) between the high and low severity hillslopes (Figure 54, Appendix 16 and Appendix 17), as demonstrated by the results of Mann Whitney tests and t-tests.

(a) Median runoff volume



(b) Mean sediment concentration

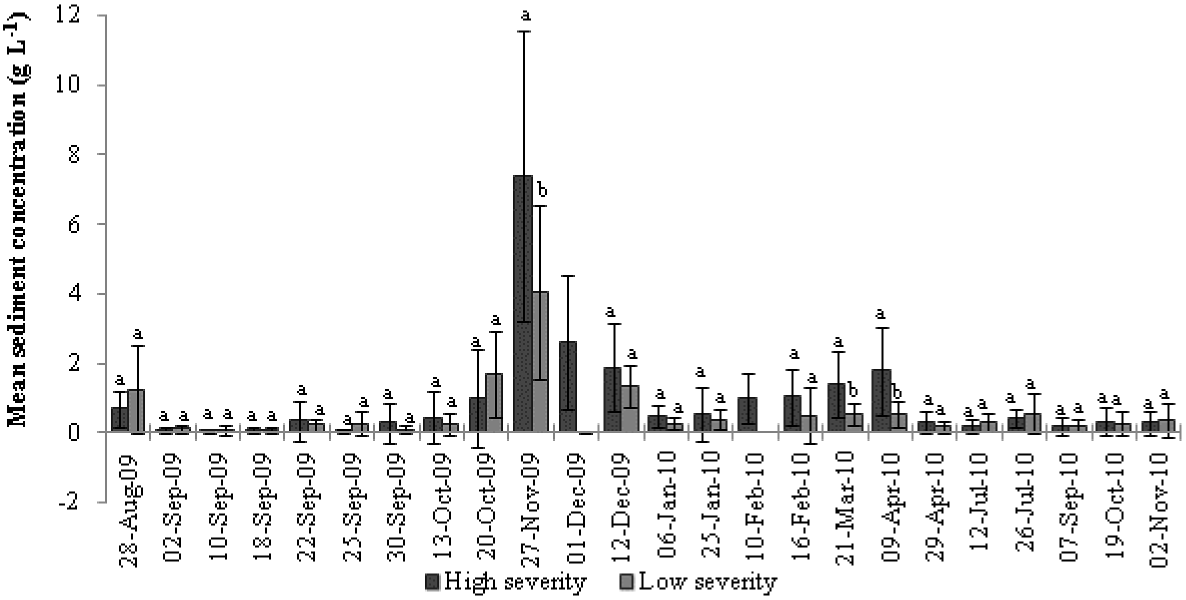


Figure 54: (a) Median runoff volumes and (b) mean sediment concentrations for each measurement date for low and high severity. Error bars for sediment concentration denote the standard deviation. Letters above the bars denote the outcome of statistical tests between the low and high severity hillslopes for a particular measurement date. Bars with the same letter were not significantly different.

7.3.5 Seasonal trends and post-fire recovery

Mean runoff ratios by season were higher in summer/autumn than in winter/spring, though statistically significant differences were only detected between summer/autumn 2009-2010 and winter/spring 2010 (Figure 55a and b). Mean sediment concentrations by season declined throughout the measurement period rather than showing a seasonal trend (Figure 55c).

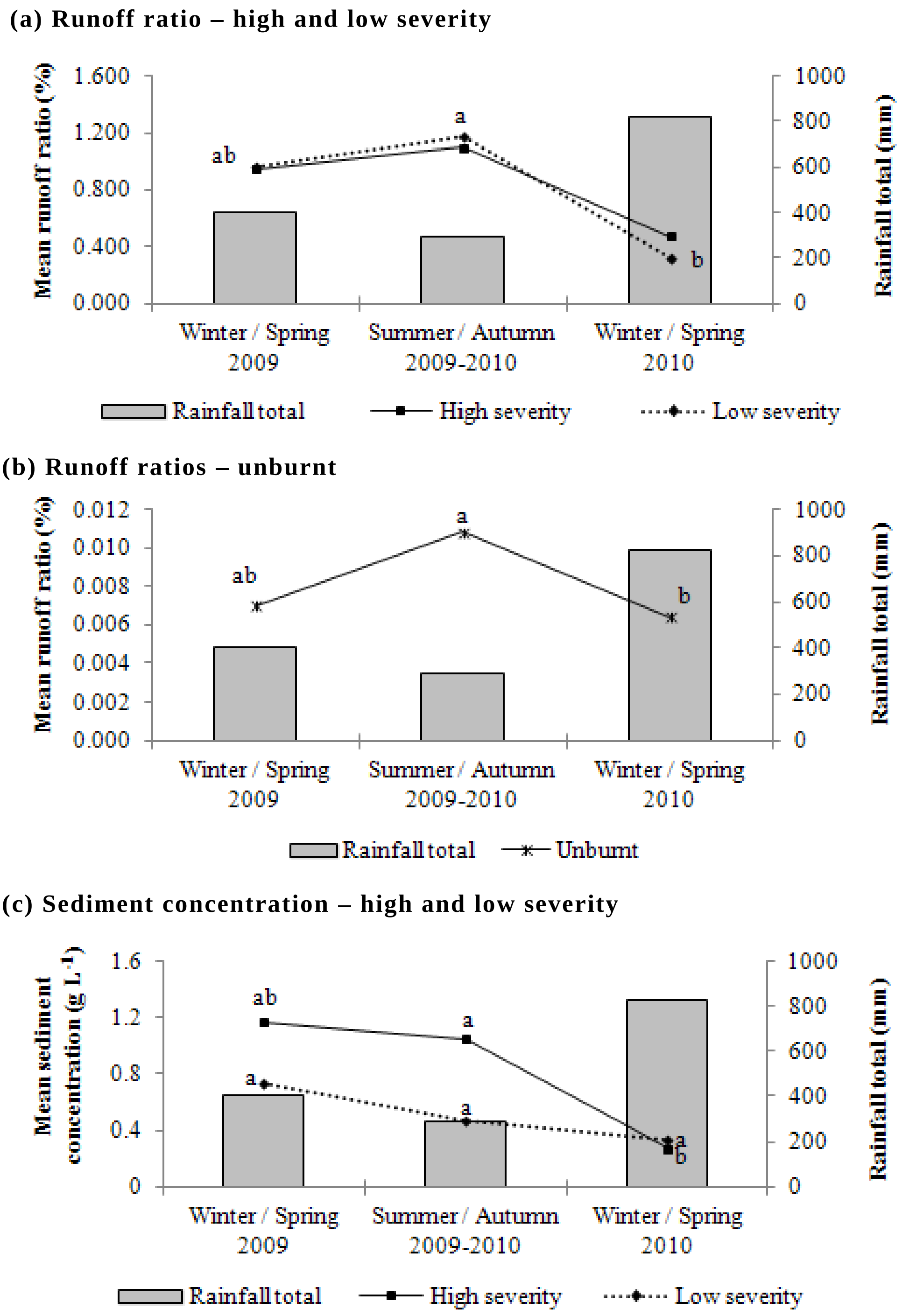


Figure 55: Mean runoff ratio by season and sediment concentration by season for unburnt, low and high severity hillslopes. Letters above the bars denote the outcome of t-tests between seasons for the same treatment. Points with the same letter are not statistically significantly different (i.e. $p > 0.05$). Unburnt sediment concentrations were not included in the analysis as there were too few rainfall events with sufficient runoff.

The double mass plots show statistically significant reductions in the rate of runoff accumulation from the burnt hillslopes (high and low severity) relative to the unburnt hillslope (Figure 56). These reductions occurred from the 27th November 2009 for the high severity hillslope and from the 29th April 2010 for the low severity hillslope. Also, there were statistically significant reductions in runoff and sediment concentrations from the low severity hillslope relative to the high severity hillslope from the 27th November 2009. The double mass plots for hillslopes with 1 m and 5 m unburnt patches show an increase in the rate of runoff accumulation relative to the unburnt and low severity hillslopes from the 27th November 2009. Similarly, the double mass plots for hillslopes with the 10 m unburnt patch also show significant increases in the rate of runoff accumulation relative to the unburnt and low severity hillslopes following particular rainfall events (i.e. after 12th December 2009 and 6th January 2012 for the unburnt and low severity hillslopes, respectively).

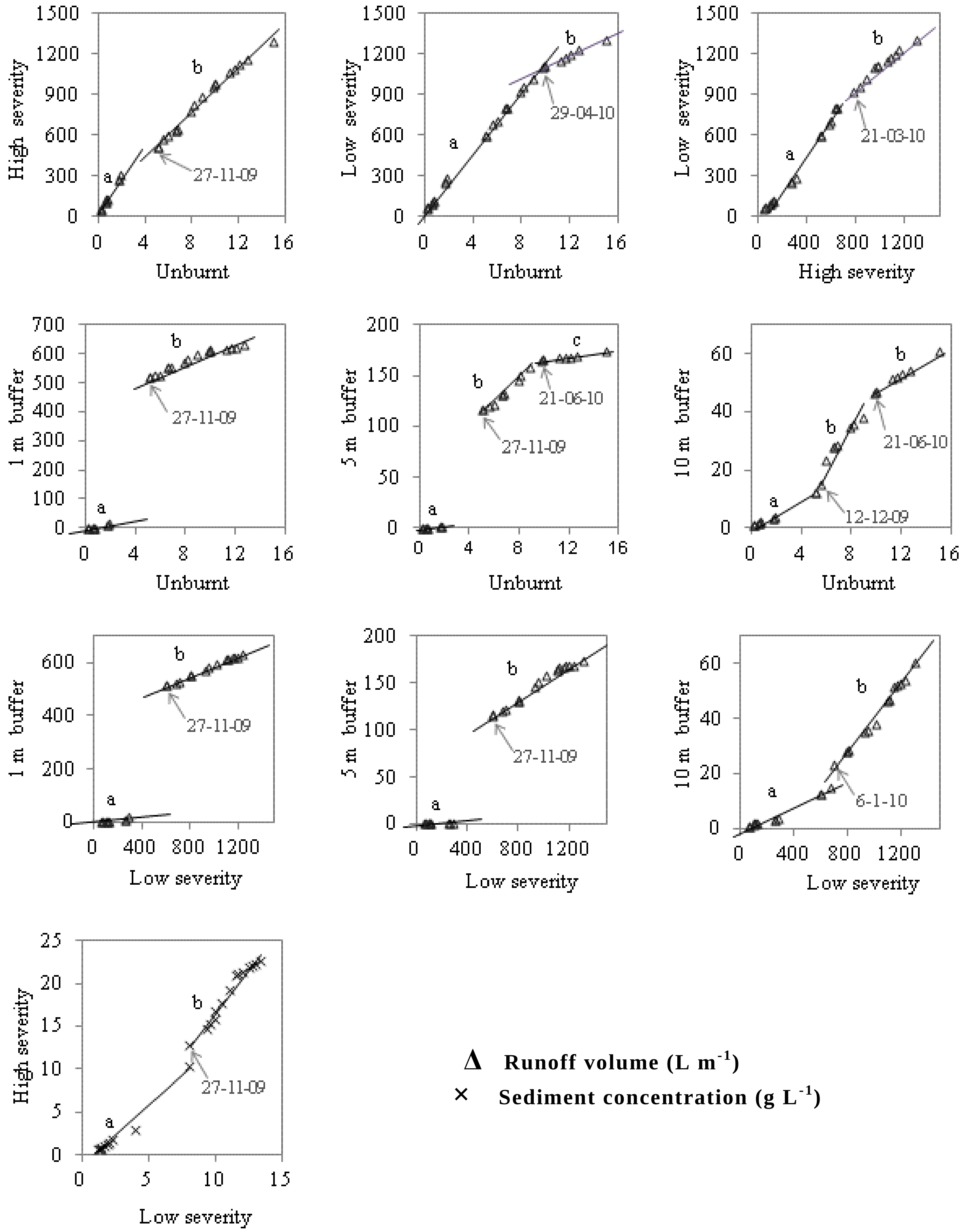


Figure 56: Double mass plots comparing hillslope treatments in terms of cumulative runoff volume (L m^{-1}) and sediment concentration (g L^{-1}). Approximate best-fit lines are drawn between the points. Letters denote the outcome of t-tests to determine whether changes in gradient were significantly different (i.e. p < 0.05). Sediment concentration data are only shown for the high and low severity hillslopes because there was insufficient sediment collected on the other hillslopes to enable a meaningful analysis to be carried out. Note differences in scale on the axes.

7.3.6 Effect of rainfall intensity on sediment load

Exponential relationships between rainfall intensity (I_{30}) and sediment load (*S*) show that the sediment loads from burnt and unburnt areas were low when the rainfall intensity was low (i.e. $I_{30} < 15$ mm h^{-1}) (Figure 57). There were substantial increases in the sediment load when the rainfall intensity exceeded approximately 20 mm h^{-1} on burnt hillslopes, but not on the unburnt hillslope. These relationships were heavily influenced by a particularly intense rainfall event recorded on the 27th November 2009.

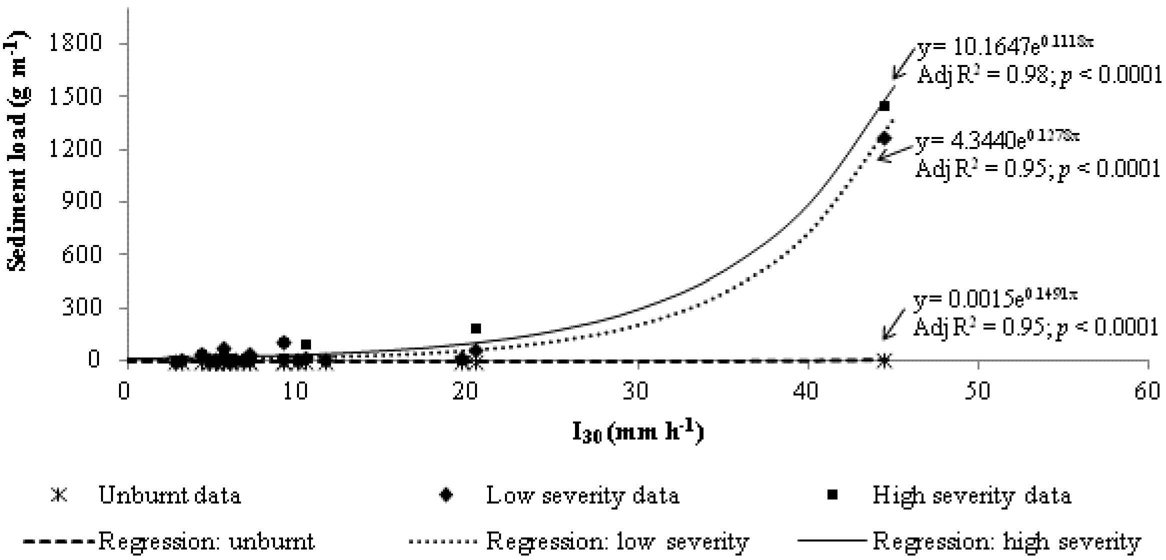


Figure 57: Relationship between rainfall intensity (I_{30}) and sediment load (*S*) for high severity, low severity and unburnt hillslopes.

Figure 58 shows negative exponential relationships between unburnt patch width and the mean reduction in sediment load for different rainfall intensities: ARI ≤ 1 year, ARI = 10 years and ARI = 10 + x years (hypothetical storm of very high intensity). For the lower rainfall intensities (ARI ≤ 1 year) unburnt patches downslope of burnt hillslopes were able to trap most of the runoff and erosion generated from the upslope burnt areas. However, with increasing rainfall intensity (ARI = 10 years and ARI = 10 + x years) narrow unburnt patches (e.g. 1 m wide) became ineffective and only the wider patch sizes trapped all the runoff and erosion. Presumably for the most severe storms all unburnt patch widths would be ineffective at substantially reducing runoff and erosion connectivity.

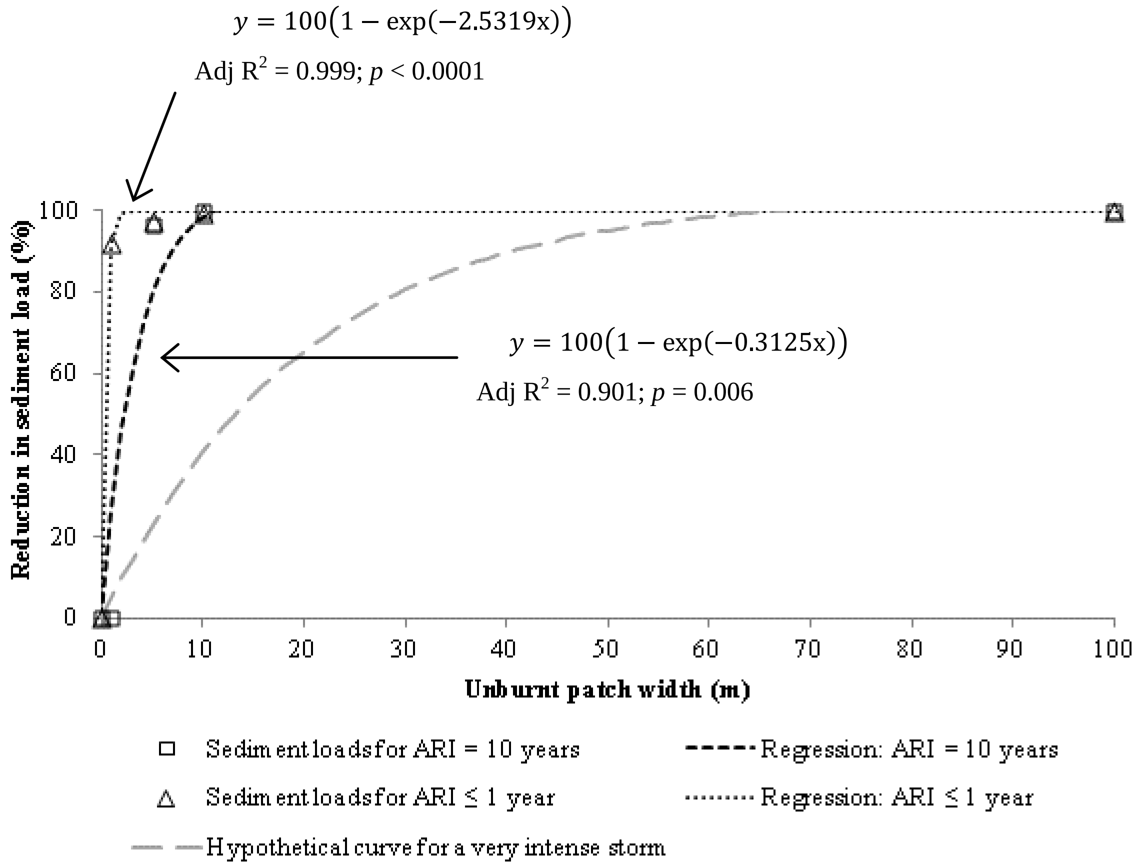


Figure 58: Regressions between unburnt patch width and mean reduction in sediment load for storms with different ARIs. The reductions in sediment loads shown for ARI = 10 years are based on the sediment loads for the 27th November 2009 measurement date; the reductions in sediment loads for ARI ≤ 1 year are based on the means of the sediment loads for the remaining rainfall events.

7.4 Discussion

This chapter has quantified the effects of fire severity and burn patchiness on runoff and erosion at the hillslope-scale. The outcomes in relation to the hypotheses are summarised in Table 29.

Table 29: A summary of Chapter 7 results in relation to each hypothesis.

Hypothesis	Outcome	Explanation
Surface runoff:		
Prescribed burning increases runoff (Hypothesis C)	Accepted	Cumulative runoff volumes were approximately two orders of magnitude greater on the burnt compared with unburnt hillslopes.
Increases in runoff rates following prescribed burning are related to the fire severity (Hypothesis C1)	Rejected	There was relatively little difference in cumulative runoff volumes between the high and low severity hillslopes (a difference of 7 L m^{-1} over 16-months).
Runoff rates recover fully within 18-months of prescribed burning (Hypothesis C2)	Rejected	Runoff rates remained substantially higher on the burnt compared with the unburnt hillslopes 18-months post-burn, despite declining during the study.
Surface erosion:		
Prescribed burning increases erosion (Hypothesis D)	Accepted	Cumulative sediment loads were approximately three orders of magnitude greater on the burnt hillslopes compared with the unburnt hillslope.
Increases in erosion rates following prescribed burning are related to the fire severity (Hypothesis D1)	Partially rejected	There was only a small difference in cumulative sediment load between the high and low severity hillslopes (a difference of 387 g m^{-1} over 16-months).
Erosion rates recover fully within 18-months of prescribed burning (Hypothesis D2)	Rejected	Erosion rates remained substantially higher on the burnt compared with the unburnt hillslopes 18-months post-burn, despite declining during the study.
Runoff and erosion connectivity:		
Connectivity of surface runoff and erosion following prescribed burning depends on the size and arrangement of fire severity and unburnt patches (Hypothesis E)	Accepted	Unburnt patches were highly effective at reducing the connectivity of runoff and erosion along hillslope flow paths. For example, there was a total sediment reduction of 99.8% for the 10 m unburnt patch. The amount of runoff and erosion connecting to a hillslope outlet is likely to depend on the size and arrangement of unburnt patches, and the rainfall properties. Since runoff and erosion rates were similar in low and high severity patches, the spatial arrangement of patches of varying fire severity (without unburnt patches) is unlikely to be important for runoff and erosion connectivity.

7.4.1 The effects of burning on runoff and erosion

Runoff and erosion rates were minimal from the unburnt hillslope. The average runoff ratio (*RO*) was 0.01% and the cumulative sediment load (*SO*) was 1.5 g m^{-1} (1.1 g m^{-1} y^{-1}). Other studies also report low runoff and erosion rates from unburnt eucalypt forests. For example, in mixed-species eucalypt forests Bren and Turner (1979) measured hillslope runoff ratios of < 0.5% in north-eastern Victoria; Ronan (1986) measured plot-scale (20 m^2) runoff ratios of 0.5-1.3% in central Victoria; Prosser and Williams (1998) measured hillslope sediment yields of 12 g m^{-1} y^{-1} in the Blue Mountains of NSW; and Inbar *et al.*(1998) measured hillslope sediment yields of 0.5 g m^{-1} y^{-1} at Mt Carmel in Israel (Table 30).

Total sediment loads from the high severity (2058 g m^{-1}) and low severity (1671 g m^{-1}) hillslopes were approximately three orders of magnitude larger than from the unburnt hillslope. Other studies also reported large increases in runoff and erosion in burnt areas (Table 30). For example, Prosser and Williams (1998) found that the sediment load increased by nearly two orders of magnitude following burning in the Blue Mountains (NSW, Australia) and Inbar *et al.* (1998) found that sediment loads increased by approximately one to four orders of magnitude following burning a site on Mt Carmel in Israel.

7.4.2 The effects of fire severity on runoff and erosion

Differences in runoff and erosion between the low and high fire severity hillslopes were small relative to differences between fire severities reported in other studies (Table 30), and the differences between burnt and unburnt hillslopes reported in this study. For example, average runoff ratios were the same (0.86%) for both severities (Table 28), and cumulative sediment loads were only 1.2 times larger for the high severity compared with the low severity hillslope. In contrast, Benavides-Solorio and MacDonald (2005) reported sediment loads that were approximately 40-200 times larger for high compared to low severity hillslopes in the Colorado Front Range (USA); Inbar *et al.* (1998) reported sediment loads that were approximately 214 times larger for high compared to low severity hillslopes at Mt Carmel (Israel); and Dragovich and Morris (2002) reported sediment loads that were approximately twice as large for high severity compared with moderate severity hillslopes in the Blue Mountains (Australia) (Table 30).

The similarity between the severities in terms of runoff and erosion in the present study probably reflects similarities in surface vegetation cover. As demonstrated in Chapter 6, surface vegetation cover is likely to be an important determinant of post-fire runoff and erosion rates and surface cover was similar on the high and low severity hillslopes throughout the measurement period (Figure 43 in Chapter 6). Another potential explanation is that the hillslopes were planar, whereas the hillslopes in other studies may not have been planar. Benavides-Solorio and MacDonald (2005) found that sediment yields were 3-4 times larger in swales than on planar hillslopes following the Bobcat fire in the Colorado Front Range.

Table 30: Selected studies reporting post-fire sediment loads using open plots for hillslopes with different fire severities. All studies were post-wildfire (rather than prescribed burn) with the exception of the current study and Benavides-Solorio and MacDonald (2005).

Author	Location	Site description	Study design	Study duration	Fire severity	Sediment load for study duration (g m^{-1})	Annual sediment load (g m^{-1} y^{-1})
Current study	Upper Yarra, Australia	Open eucalypt forest with shrub understorey	Plots 10 cm wide; 20 plots per hillslope treatment	16-months	High severity	2057.9	1543.4
					Low severity	1671.4	1253.6
					Unburnt	1.5	1.1
Prosser and Williams (1998)	Blue Mountains, Australia	Open eucalypt forest with shrub understorey	Plots 2 m wide; 4 plots per hillslope treatment; approximate hillslope length was 100 m	10-months	Moderate severity – canopy scorched, understorey burnt	770	924
					Unburnt	10	12
Dragovich and Morris (2002)[A]	Blue Mountains, Australia	Open eucalypt forest with shrub understorey	Plots 2 m wide; 2 plots per hillslope treatment	6-months	High severity – all vegetation burnt	610	1220
					Moderate severity – canopy partially burnt, understorey burnt	330	660
					Low severity – prescribed burnt two years earlier	40	80
Benavides-Solorio and MacDonald (2005)	Colorado Front Range, USA	Ponderosa pine and lodgepole pine forest	Sediment fences 8 m wide; 48 fences in total; average hillslope length of 68 m	18-months	High severity – surface fuels burnt, soil visibly altered	20400 - 102000	13600 – 68000
					Moderate severity – surface fuels burnt, soil not visibly altered	2040	1360
					Low severity – surface fuels partially consumed	510	340
Inbar *et al.* (1998) [B]	Mt Carmel, Israel	Maquis scrub	Plots 8 m wide; 4 plots per hillslope treatment; contributing area of 100-400 m^2	3 years	High severity – no description	12850	11700[C]
					Low severity – no description	60	40[C]
					Unburnt	3	0.5 [C]

[A] Only slope-wash data included – the study also measured the quantity of sediment transported downslope by bioturbation; [B] Only results from hillslopes with southerly aspects reported; [C] Data for first year post-burn

7.4.3 Seasonal trends and post-fire recovery

Seasonally averaged runoff ratios and sediment concentrations calculated by season (summer/autumn versus winter/spring) revealed seasonal fluctuations in runoff but not erosion (Figure 55). Seasonally averaged runoff ratios were higher in summer/autumn despite lower rainfall totals at this time of year, possibly reflecting higher water repellency (Chapter 4) and low infiltration capacities (Chapter 5) at this time. Few studies consider seasonal trends in runoff and erosion at the hillslope-scale, but seasonal trends in hydrologic properties such as water repellency are often reported (e.g. Keizer *et al.* 2008; Sheridan *et al.* 2007).

Runoff and erosion rates were higher on the burnt hillslopes relative to the unburnt hillslope for the duration of the study. However, there was a decline in runoff rates relative to unburnt areas (after the 27th November 2009 and 9th April 2010 for the high and low severity hillslopes, respectively) (Figure 56) and seasonally averaged sediment concentrations also appeared to decline over time (Figure 55). Other studies also report long time lags between burning and the full recovery of runoff and erosion rates. For example, Inbar *et al.* (1998) predicted that a period of 5-10 years would be required for burnt areas to recover fully, Prosser and Williams (1998) found that ground cover had not fully recovered two years after fire, and Benavides-Solorio and MacDonald (2005) found that the percent bare soil was higher in moderate and high severity areas compared with low severity areas seven years following prescribed burning. The statistically significant reduction in sediment concentration from the low severity hillslope relative to the high severity hillslope from the 27th November 2009 (Figure 56) may reflect more rapid sediment exhaustion on the low severity hillslope.

7.4.4 Effects of rainfall intensity

Much of the runoff and sediment were generated from a few storms. For example, 22%, 24% and 15% of the cumulative runoff volume for the unburnt, low and high severity hillslopes, respectively, were measured on the 27th November 2009. Conversely, for rainfall totals < 5 mm there was little, if any, runoff. Other studies have reported similar differences in runoff and erosion rates between rainfall events. For example, Inbar *et al.* (1998) found that 90% of the erosion for the second year post-burn occurred during one day of high intensity rain, while there was no runoff generated for rainfall intensities < 10 mm h^{-1}; Lane *et al.* (2006) reported that 50% of the post-fire sediment load over two years was delivered during one intense summer thunderstorm, while 75% was generated from two events; Kunze and Stednick (2006) reported that two events accounted for about 90% of the post-fire sediment load; Prosser and Williams (1998) reported that there was no runoff for rainfall totals < 5 mm and that sediment yields were related to the rainfall intensity.

For individual measurement dates in the present study, mean sediment concentrations were always significantly larger and median runoff volumes usually so for burnt hillslopes compared with the unburnt hillslope. In a few instances where runoff volumes were very low due to low rainfall totals, median runoff volumes were not significantly different between burnt and unburnt areas. Differences in runoff and erosion between the low and high severity hillslopes were usually not statistically significant with the exception of some rainfall events where the totals were very high or very low, or where the intensities were very low.

7.4.5 **The effects of burn patchiness on runoff and erosion connectivity**

Unburnt patches were variable in their effectiveness at reducing runoff and erosion connectivity. Cumulative runoff volumes were reduced by 48.5%, 86.7% and 95.4% and cumulative sediment loads were reduced by 1.5%, 96.6% and 99.8% by the 1 m, 5 m and 10 m wide unburnt patches, respectively (Table 28). These figures demonstrate a clear relationship between patch width and the percentage of runoff and sediment trapped by the unburnt patch. Other studies also report reductions in sediment loads downslope of vegetated patches (Cerdà 1997; Dosskey 2001; Helmers *et al.* 2005; Mayor *et al.* 2009), though there have been no comparable studies carried out in burnt environments. In a semi-arid environment, Bartley *et al.* (2006) reported a hillslope runoff ratio of 71% when there was a large bare patch near the base of the hillslope, compared with a runoff ratio of 8% for a hillslope with uniformly distributed bare and vegetated patches. In modelling simulations, Reaney (2003) predicted that no runoff would reach the bottom of a hillslope if there was a five metre vegetated strip at its base for a 75 mm h^{-1} rainfall event lasting for five minutes. For pastoral lands, Leguédois *et al.*(2008) reported that runoff volumes were reduced by 28-62% and sediment loads by 90% downslope of tree belts. Factors thought to influence the performance of vegetated buffers are the amount of eroded sediment from upslope, vegetation density and structure, overland flow rate, sediment particle size, buffer width and slope gradient (Hairsine 1997). Studies in pastoral lands have found that most sediment deposition occurs within the first few metres of a vegetated strip (Dosskey 2001; Yuan *et al.* 2009; Zhang *et al.* 2010), which may explain why there was often little difference in buffer effectiveness between the 5 m and 10 m wide unburnt patches at Upper Yarra.

The measurements from hillslopes with unburnt patches highlight a potential limitation of point and plot-scale studies in supporting inferences at hillslope and catchment-scales. The data suggest that runoff and erosion rates at the hillslope or catchment-scale cannot be predicted from a simple tally of burnt and unburnt area because the spatial arrangement of the burnt and unburnt areas is a highly significant factor. Prescribed burns often have unburnt patches, especially in riparian zones (Penman *et al.* 2007). This may explain why large increases in instream suspended sediment loads are rarely reported following prescribed burning despite plot scale studies reporting large increases. As discussed in Chapter 2, catchment-scale studies following prescribed burning generally report minimal impacts on instream suspended sediment concentrations (e.g. Scott 1993; Smith *et al.* 2010; Townsend and Douglas 2000), while plot-scale studies more frequently report impacts (e.g. Benavides-Solorio and MacDonald 2001; Robichaud 2000; Robichaud *et al.* 2007).

The percentage reduction in sediment was related to rainfall intensity, especially for the 1 m unburnt patch where the proportion of runoff / sediment trapped ranged from 92% for rainfall events with an ARI of $\leq$ 1 year, to zero for rainfall events with an ARI of 10 years (Figure 58). Concentrated flow associated with higher rainfall intensities is thought to reduce the effectiveness of vegetated strips in agricultural land (Dosskey 2001; Hairsine 1997; Helmers *et al.* 2005). While there was no evidence of concentrated flow at Upper Yarra in the form of rills, leaf litter within the unburnt patches appeared to have moved into heaps during the most intense rainfall events, which may have helped channel runoff across the soil surface more efficiently. Importantly, after the intense storms associated with the 30th

September 2009 and 27th November 2009, the 1m and 5 m unburnt patches appeared to be less effective at reducing runoff and erosion during subsequent rainfall events. Dosskey *et al.* (2001) have discussed the need to maintain the effectiveness of vegetated strips in agricultural settings over time by the periodic removal of sediment and other modifications to surface microtopography. It would be impractical to maintain vegetated patches in prescribed burnt forests in such a way, but if large rainfall events do reduce their effectiveness, then larger patches may be required to reduce runoff and erosion over longer periods.

7.5 Conclusion

Prescribed burning increased the hillslope sediment load by approximately three orders of magnitude over the duration of the study as indicated by the cumulative sediment load of 1.5 g m^{-1} on the unburnt hillslope compared with 2058 g m^{-1} and 1671 g m^{-1} on the high and low severity hillslopes, respectively. In contrast, differences between the severities in terms of cumulative sediment loads were small. These results suggest that while burning causes higher runoff and erosion rates, fire severity is not a major determinant of the magnitude of these increases, at least with regard to prescribed burning.

Unburnt patches were variable in their effectiveness at reducing runoff and erosion from upslope burnt areas, with runoff volumes being reduced by 48.5 - 95.4% and sediment loads by 1.5 – 99.8%. The reduction in runoff volume and sediment load downslope of an unburnt patch varied with patch width and rainfall intensity. Not surprisingly, the 10 m patch width was most effective – sediment loads collected downslope of this patch were not much higher than amounts from the unburnt hillslope, even during the most intense storms. In contrast, the 1 m patch width was least effective and the proportion of runoff and sediment it trapped varied dramatically depending on the rainfall intensity. Sediment reduction was 0% sediment reduction for the 27th November 2009 measurement date compared with an overall reduction of 92% for the other measurement dates, which had ARIs $\leq$ 1 year. These results suggest that unburnt patches may explain why increases in instream suspended sediments are rarely reported following prescribed burning at the catchment-scale, despite plot-scale studies often reporting large impacts.

8. Overall discussion and conclusions

8.1 Introduction

This thesis has tested a conceptual model about the role of fire severity and burn patchiness to quantify the effects of prescribed burning on soil hydrologic properties, surface runoff and erosion. Fire severity and burn patchiness were identified in the literature review (Chapter 2) as potentially important fire regime characteristics influencing post-fire runoff and erosion. The conceptual model (Chapter 3) proposed that the volumes of hillslope-derived surface runoff and erosion entering a stream following prescribed burning depend on: (1) hydrological and erosional processes occurring within patches, which vary according to whether and how severely the patches have been burnt, and (2) the spatial interaction between the patches. Hypotheses were devised from the conceptual model (Figure 10 in Chapter 3) and tested at different spatial scales in the results chapters (Chapters 4-7). Overall, the results showed that:

- Runoff and erosion rates were substantially higher in burnt compared with unburnt patches
- Fire severity had relatively little effect on post-fire runoff and erosion
- Unburnt patches were highly effective at reducing surface runoff and erosion connectivity from upslope burnt areas
- Runoff and erosion rates did not fully recover 18-months post-burn.

This chapter discusses the evidence supporting those results, the properties and processes contributing to the observed outcomes, and the implications both conceptually (as illustrated in the revised conceptual model – Figure 59, Figure 60 and Figure 61) and from a management perspective. The discussion focuses on the results from Upper Yarra with the results from Big Ben and Mt Cole used for extrapolating beyond the Upper Yarra site.

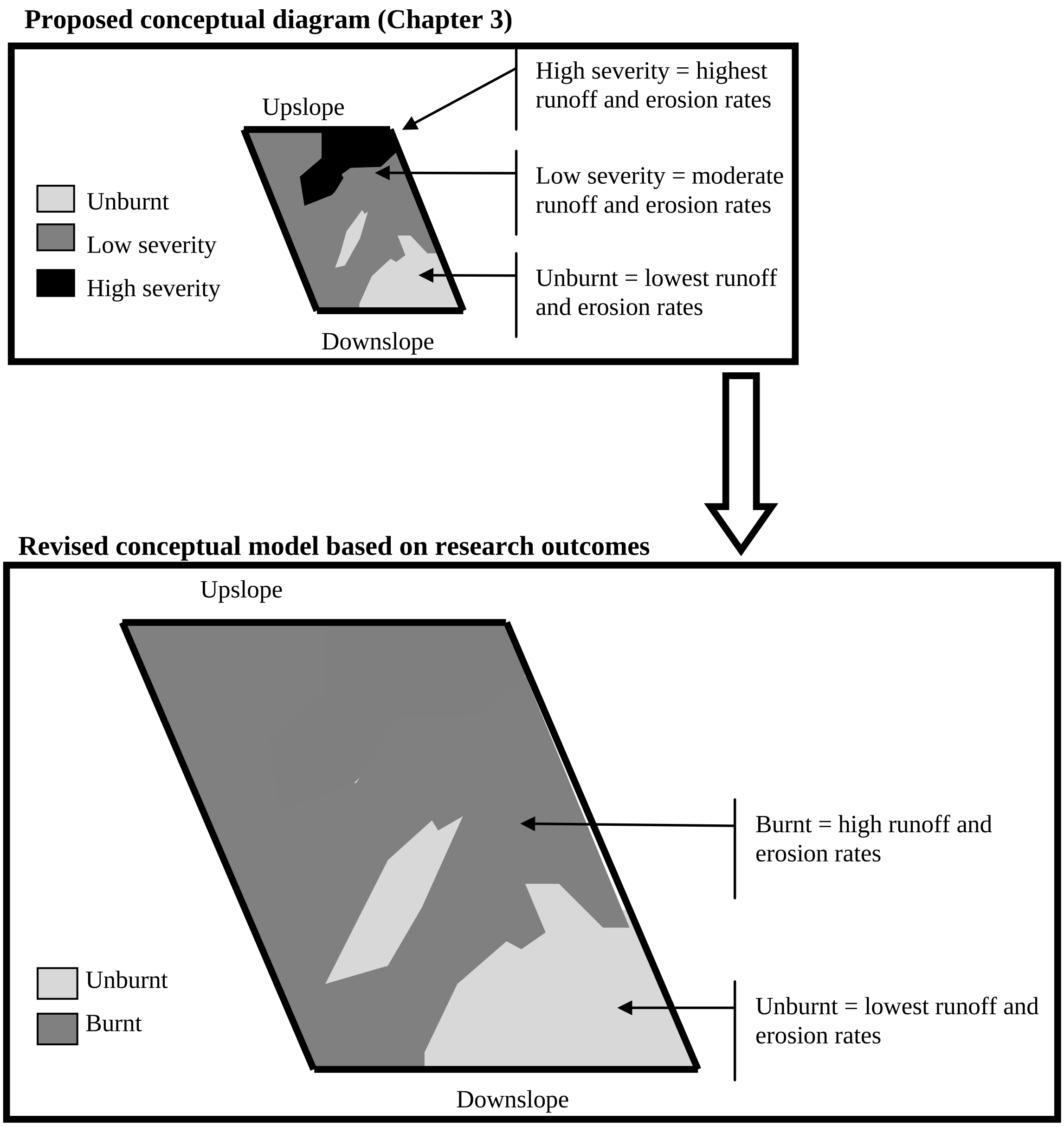
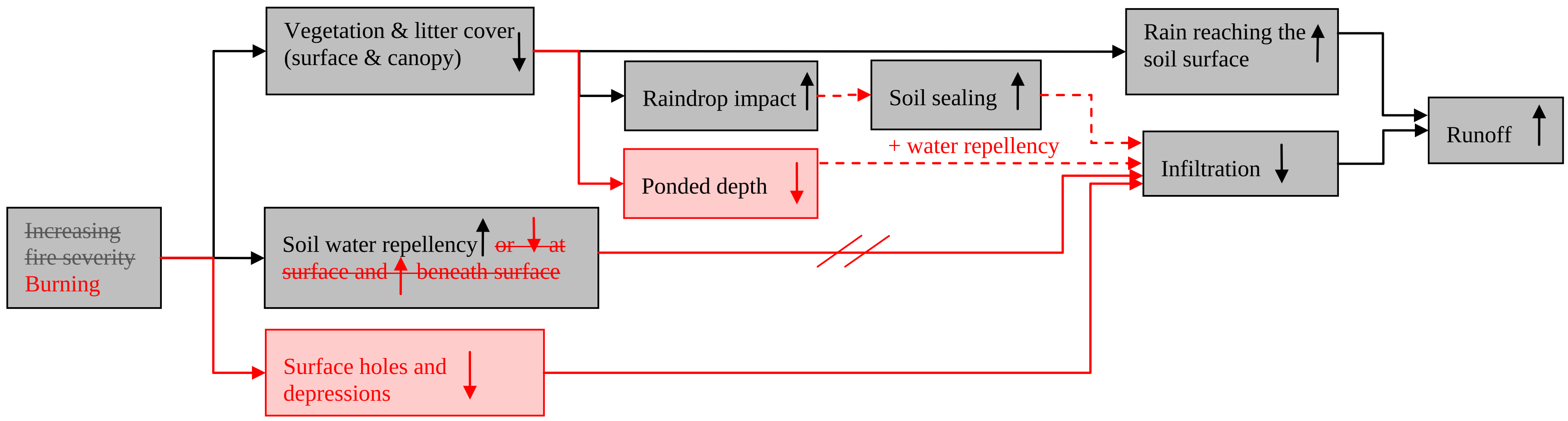


Figure 59: A revised conceptual diagram showing a prescribed burnt hillslope with burnt and unburnt patches. The burnt patches are sediment generating areas and the unburnt patches are sediment sinks. The amount of runoff and erosion reaching the bottom of the hillslope depends on the size and spatial arrangement of the burnt and unburnt patches.

(a) Effects of burning on runoff: Proposed conceptual diagram from Chapter 3 with annotated changes based research outcomes



(b) Effects of burning on runoff: Revised conceptual diagram

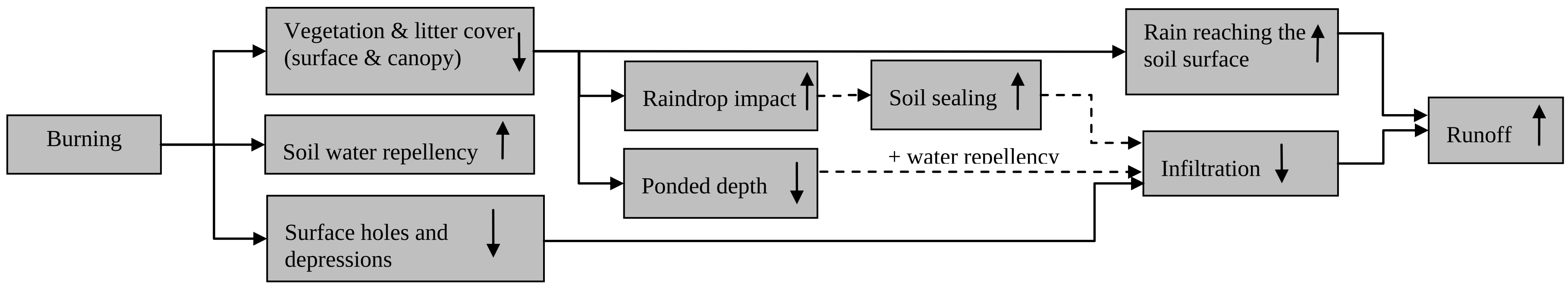
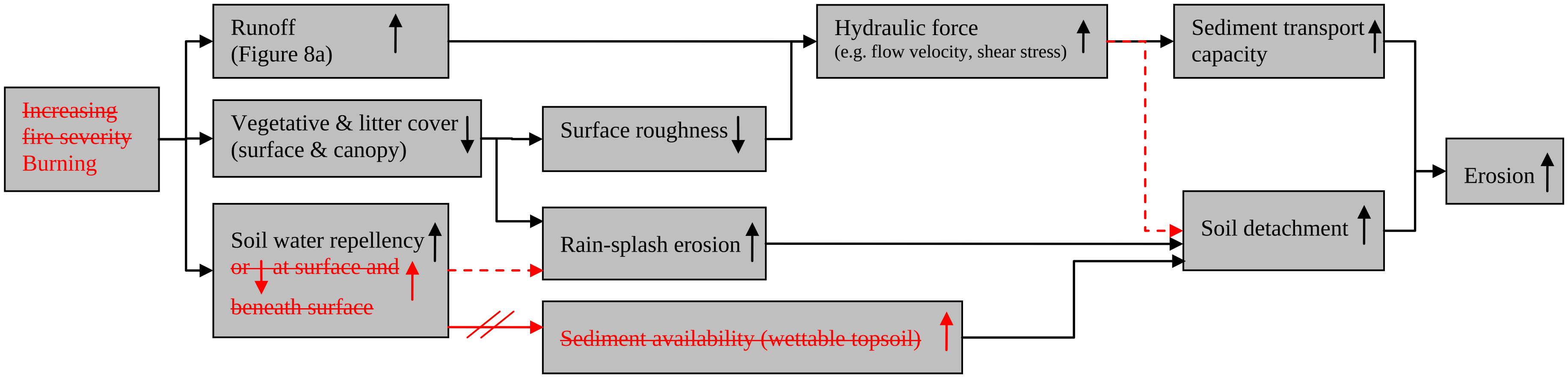


Figure 60: Revised conceptual diagram showing the effects of burning on runoff. (a) Proposed conceptual diagram presented in Chapter 3 with annotated changes (in red) based on the research outcomes of this thesis. (b) Fully revised conceptual diagram. Arrows within the boxes show the expected change to that property or process as a result of burning. Solid lines between boxes show relationships that were supported by the data. Dashed lines between boxes show relationships that were neither supported nor rejected by the data.

(a) Effects of burning on erosion: Proposed conceptual diagram from Chapter 3 with annotated changes based on research outcomes



(b) Effects of burning on erosion: Revised conceptual diagram based on research outcomes

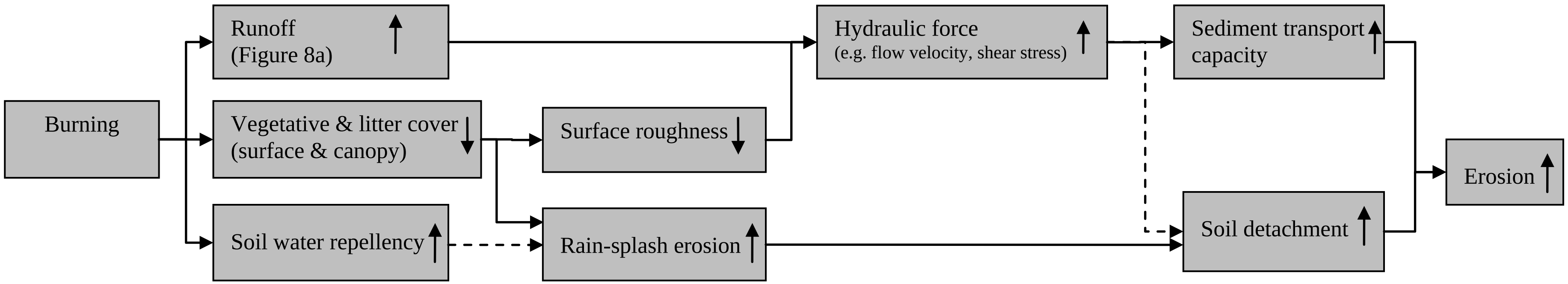


Figure 61: Revised conceptual diagram showing the effects of burning on erosion. (a) Proposed conceptual diagram presented in Chapter 3 with annotated changes (in red) based on the research outcomes of this thesis. (b) Fully revised conceptual diagram. Arrows within the boxes show the expected change to that property or process as a result of burning. Solid lines between boxes show relationships that were supported by the data. Dashed lines between boxes show relationships that were neither supported nor rejected by the data.

8.2 The effects of burning

The results from Upper Yarra showed clearly that burning increases the potential for surface runoff and erosion (Table 31). At the plot-scale, steady-state runoff ratios were approximately 15-20% higher for burnt compared with unburnt plots and steady-state sediment concentrations were almost an order of magnitude higher for burnt plots (Chapter 6). At the hillslope-scale, overall runoff ratios were almost two orders of magnitude higher on burnt compared with unburnt hillslopes while overall sediment loads were approximately three orders of magnitude higher on burnt hillslopes (Chapter 7). As discussed in Chapters 6 and 7, these results agree with numerous other studies that also report higher runoff and erosion rates in burnt areas (see reviews by Certini 2005; Shakesby 2011; Shakesby and Doerr 2006; Shakesby *et al.* 2007; Smith *et al.* 2011c; Wondzell and King 2003).

Table 31: Results for hypotheses relating to the effects of prescribed burning.

Hypothesis	Critical surface tension (Chapter 4)	Infiltrometer measurements (Chapter 5)	Rainfall simulations (Chapter 6)	Runoff samplers (Chapter 7)
Prescribed burning increases soil water repellency (Hypothesis A)	Accepted[A]	---	---	---
Prescribed burning reduces infiltration (Hypothesis B)	---	Rejected	Accepted	---
Prescribed burning increases runoff (Hypothesis C)	---	---	Accepted	Accepted
Prescribed burning increases erosion (Hypothesis D)	---	---	Accepted	Accepted

[A] Hypothesis only accepted at Upper Yarra and Mt Cole, not Big Ben.

8.2.1 Loss of vegetative cover

The revised conceptual model (Figure 60 and Figure 61) identifies the loss of vegetation cover as an important factor contributing to higher runoff and erosion rates in burnt areas. Vegetation cover was substantially less in burnt areas declining from 85% pre-burn to 0-18% post-burn at Upper Yarra (Chapter 6). Regression curves calculated for the rainfall simulation data showed a linear relationship between the runoff ratio and the percentage bare soil / ash, and an exponential relationship between the sediment concentration and the percentage bare soil / ash (Chapter 6). As discussed throughout the thesis, other studies have also reported strong relationships between vegetation cover, surface runoff and erosion (e.g. Benavides-Solorio and MacDonald 2001; Benavides-Solorio and MacDonald 2005; Cerdà 1998; Cerdà and Doerr 2005; Johansen *et al.* 2001; Larsen *et al.* 2009; Leighton-Boyce *et al.* 2007). The loss of vegetative cover is likely to have caused increased runoff and erosion at Upper Yarra as a result of at least one of the following mechanisms:

- Reduced rainfall interception – surface water storage capacities were 2 mm for unburnt litter versus 1.4 mm for ash (Chapter 6).
- Soil sealing – the potential for soil sealing to occur is higher on exposed soil surfaces (Larsen *et al.* 2009), though its effects on infiltration and runoff were not isolated from other factors in this study and thus have been inferred.
- Reduced ponded depth – this is a feasible explanation for lower infiltration capacities in burnt areas since infiltration capacities in water repellent soils are highly sensitive to ponded depth (discussed in Chapter 6).
- Rain-splash erosion – soil pedestals throughout the burnt areas (Chapter 7) are evidence that rain-splash erosion had occurred. Erosion rates by this mechanism were quantified in Chapters 6 and 7 and found to be much higher in burnt areas.
- Increased hydraulic force – higher flow velocities were measured in burnt areas (Chapter 6) and are likely to have increased the sediment transport capacity of runoff.
- Enhanced effects of soil water repellency – it is likely that the loss of vegetative cover enabled water repellency to affect erosion to a greater extent in burnt areas than in unburnt areas, though the effects of water repellency on erosion were not isolated from other factors in this study (discussed in Chapter 6).

8.2.2 **Increased soil water repellency**

There was no evidence supporting a direct relationship between fire-induced increases in water repellency and reduced infiltration capacities. Infiltration capacities measured with the infiltrometer were not significantly different between burnt and unburnt areas at any time following the burn (Chapter 5) despite increased water repellency in burnt areas at Upper Yarra and Mt Cole (Chapter 4). In contrast, infiltration capacities appeared to be affected by seasonal trends in water repellency and strong pre-existing water repellency. As discussed in Chapter 5, this result suggests that seasonally-induced changes to water repellency affected infiltration capacities differently to fire-induced changes to water repellency (potential explanations are discussed in Chapter 5).

The effects of water repellency on erosion rates were not isolated from the effects of reduced vegetation cover. Water repellency is thought to enhance erosion rates by improving rain-splash effectiveness (Shakesby *et al.* 2000; Terry and Shakesby 1993). It is likely that the loss of vegetation cover was the main catalyst for erosion in burnt areas, while water repellency merely added to the magnitude of the erosion rate. Water repellency did not appear to enhance erosion in unburnt areas, since erosion rates in unburnt areas were very low despite widespread water repellency (Chapter 6 and 7).

8.2.3 **Scaling effects**

A significant feature of the results was that the magnitude differences in runoff and sediment concentrations between burnt and unburnt areas were much larger at the hillslope-scale compared with the plot-scale. Runoff ratios were 15-20% higher in burnt areas at the plot-scale (Chapter 6) compared with almost two orders of magnitude higher at the hillslope-scale (Chapter 7). Sediment concentrations were approximately an order of magnitude higher for burnt areas at the plot-scale (Chapter 6) compared with approximately three orders of magnitude higher at the hillslope-scale (Chapter 7). Potential explanations for these discrepancies include: (1) differences in rainfall intensity between plot and hillslope-scale measurements, and (2) more interruptions to runoff connectivity at the hillslope-scale.

Very high rainfall intensities used during the rainfall simulations (60 mm h^{-1} and 100 mm h^{-1}) are likely to have reduced the magnitude differences in runoff and erosion between the burnt and unburnt plots. As infiltration rates and erosion rates reached (or neared) their maximum potential values, any additional rainfall was arrested in its entirety to become runoff, reducing the apparent differences in runoff rate and sediment concentration between the treatments (Figure 62). In contrast, for the runoff sampler measurements most rainfall events were of relatively low intensity (mean I_{30} of 9.2 mm h^{-1}). Often during these events only the burnt areas produced runoff as the infiltration capacities were not exceeded in the unburnt plots. As a result, there were usually very large magnitude differences in runoff and sediment concentration between the treatments.

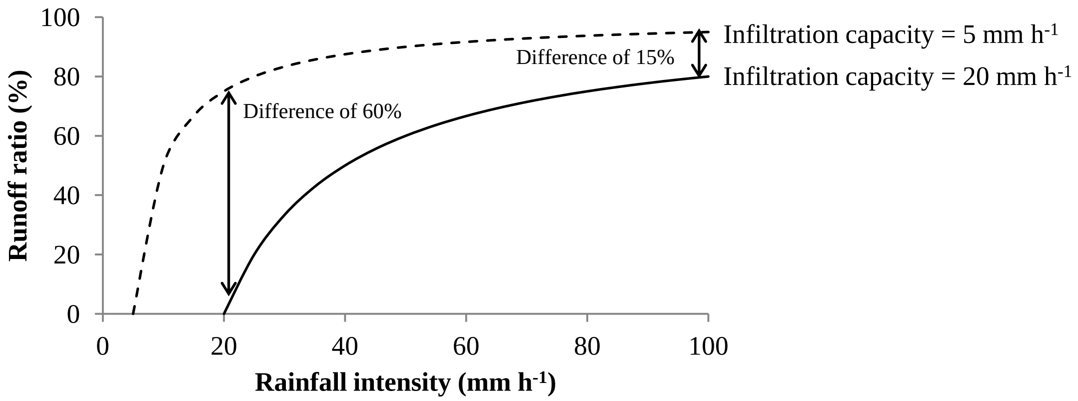


Figure 62: Hypothetical curves to illustrate the effect of increasing rainfall intensity on the magnitude difference in steady-state runoff ratios between soils with different infiltration capacities.

Surface holes and depressions caused by bioturbation, burnt-out stumps or soil cracking are likely to have reduced runoff and acted as a sediment store at the hillslope-scale. As discussed in Chapter 5, these features were more common in unburnt areas and often had very high infiltration rates. The criteria used to locate rainfall simulation plots meant that these surface holes and depressions were not present at the plot-scale because uniform areas with no leaking holes were deliberately selected for the simulations (see Chapter 6). Therefore, it is likely that there were larger magnitude differences in runoff and erosion rates between burnt and unburnt areas at the hillslope-scale. Other studies also highlight the potential significance of surface holes and depressions for infiltration at larger spatial scales (Doerr *et al.* 2003; Doerr and Moody 2004; Ferreira *et al.* 2008; Shakesby *et al.* 2000; Shakesby *et al.* 2007).

These explanations are also useful for understanding another key feature of the data, the much smaller runoff ratios found at the hillslope-scale than at the plot-scale. Runoff ratios were 48-97% (steady-state values) at the plot-scale (Table 21) compared with 0.01-0.86% (average values) at the hillslope-scale (Table 28). Several studies report diminishing runoff ratios with increasing plot length (e.g. Bren and Turner 1979; Gomi *et al.* 2008). As plot length increases, the relative proportion of area connected to the plot outlet can decrease as there is a higher likelihood that there will be points along the flow path with infiltration capacities high enough for the runoff from upslope to infiltrate (Ferreira *et al.* 2008; Shakesby *et al.* 2000). This is a potential limitation of point and plot-scale studies in supporting inferences at hillslope or catchment scales. The large holes caused by bioturbation, burnt out root holes and soil cracks are one potential source of high infiltration at the hillslope-scale, and may explain the lower runoff ratios at the hillslope scale at Upper Yarra. Additionally, the relative significance of points with particularly high infiltration capacities would have been less at the plot-scale because the rainfall intensities and resulting volumes of runoff were very high.

8.3 The effects of fire severity

There was relatively little difference between the low and high severity areas at Upper Yarra in terms of soil hydrological and erosional properties and processes (Table 32). At the point-scale, water repellency (Chapter 4) and infiltration capacity (Chapter 5) were not statistically significantly different between the low and high severity burns. Similarly, at the plot-scale, differences between the severities were small. The mean steady-state runoff ratio (in autumn 2009 for the 100 mm h^{-1} simulation) differed by only 2% between the low and high severities while it was 15-17% lower for the unburnt plots; the mean steady state sediment concentration differed by just 0.6 g L^{-1} between the low and high severities while it was as much as 3.3-3.9 g L^{-1} lower for the unburnt plots (Chapter 6). At the hillslope-scale, average runoff ratios were the same for the low and high severities while they were almost two orders of magnitude lower on the unburnt hillslope. Similarly, cumulative sediment loads differed by a factor of 1.2 between the low and high severities while they were approximately three orders of magnitude higher on the burnt hillslopes compared with the unburnt hillslope.

Table 32: Results for hypotheses about the effects of fire severity.

Hypothesis	Critical surface tension (Chapter 4)	Infiltrometer measurements (Chapter 5)	Rainfall simulations (Chapter 6)	Runoff samplers (Chapter 7)
Increases in soil water repellency following prescribed burning are related to the fire severity (Hypothesis A1)	Rejected	---	---	---
Decreases in infiltration capacities following prescribed burning are related to the fire severity (Hypothesis B1)	---	Not applicable[A]	Rejected	---
Increases in runoff rates following prescribed burning are related to the fire severity (Hypothesis C1)	---	---	Rejected	Rejected
Increases in erosion rates following prescribed burning are related to the fire severity (Hypothesis D1)	---	---	Rejected	Rejected

[A] Since prescribed burning had no effect on point-scale infiltration capacities, this hypothesis was no longer applicable.

The implication of these results for the conceptual model is that fire severity is not a major factor explaining differences in runoff and erosion between burnt areas (Figure 59). This finding contrasts with several other studies that identified fire severity as an important determinant of soil hydrologic properties, runoff and erosion (e.g. Benavides-Solorio and MacDonald 2001; Benavides-Solorio and MacDonald 2005; Doerr *et al.* 2006; Dragovich and Morris 2002; Huffman *et al.* 2001; Robichaud 2000; Vadilonga *et al.* 2008; Woods *et al.* 2007). However, those studies do not necessarily disagree with the results from Upper Yarra as the fire severities considered at Upper Yarra, while encompassing the range likely to occur in a prescribed burn, did not encompass the full range of fire severities that occur in wildfire-burnt areas (Figure 20 in Chapter 3). It is possible that more extreme fire severities could have generated significantly larger hydrological and erosional responses as a result of factors such as greater soil heating, more complete consumption of the litter/duff layer and the elimination of soil aggregates. Therefore, the results of this study do not disagree with the importance of fire severity to post-fire runoff and erosion in all circumstances. However, in the context of prescribed burning the results suggest that fire severity is a relatively unimportant factor.

It is likely that the fire severities at Upper Yarra had similar hydrological and erosional responses because they had similar amounts of surface vegetation cover. The burn consumed the majority of the surface litter leaving behind ash and charred leaf fragments. Surface vegetation cover was reduced from 85% to 0-18% initially, and then increased gradually to 47-54% 18-months post-burn (Chapter 6). As discussed previously, vegetation cover (or conversely, percent bare soil) appeared to be a major driver of post-fire runoff and erosion at Upper Yarra. Other studies report more substantial differences in surface cover between fire severity classes, which may explain the larger differences in post-fire runoff and erosion between severities detected in those studies. For example, during post-fire rainfall simulations in the Colorado Front Range, sediment yields were 10-26 times higher in high severity plots compared with low severity plots; this magnitude difference was attributed to large differences in ash cover (23% versus 99% in high and low severity plots, respectively) (Benavides-Solorio and MacDonald 2001). Differences in fire-induced soil water repellency is another factor used to explain hydrological and erosional differences between fire severities in other studies (e.g. Doerr *et al.* 2006; Robichaud 2000). As discussed previously, there were no differences in water repellency between the fire severities at Upper Yarra and fire-induced water repellency did not appear to affect infiltration capacities.

8.4 The effects of burn patchiness

The conceptual model tested by the study proposed that runoff and erosion connectivity on a fire-affected hillslope is controlled by the size and spatial arrangement of different fire severity and unburnt patches. This hypothesis was supported by the results, but only in terms of burnt versus unburnt patches since there was little difference in runoff and erosion between the different fire severities, and the hillslope measurements only related to the effect of unburnt patches of different sizes. Overall, 1 m, 5 m and 10 m wide unburnt patches absorbed 1.5%, 96.6% and 99.8% of the sediment from upslope burnt areas, respectively (Chapter 7). However, for the vast majority of rainfall events (with ARIs of ≤ 1 year), the effectiveness of different patch widths were very similar with sediment loads reduced by 92.1%, 97.3% and 99.4% for the 1 m, 5 m and 10 m unburnt patches, respectively. The most intense storm recorded (I_{30} = 44 mm h^{-1}; ARI = 10 years) rendered the 1 m unburnt patch ineffective at reducing runoff and erosion connectivity, while the 5 m and 10 m unburnt patches continued to have high runoff and sediment reduction rates. As discussed in Chapter 7, other studies have also reported reductions in sediment loads downslope of vegetated patches (e.g. Cerdà 1997; Dosskey 2001; Helmers *et al.* 2005; Mayor *et al.* 2009), though there are no similar studies in burnt environments. Importantly, the effectiveness of the patches appeared to be less for the rainfall events immediately following a particularly intense storm (Figure 56 in Chapter 7). These storms appeared to move leaf litter within the unburnt patches, creating litter dams and channels for more concentrated flow, possibly making the unburnt patches less effective during future events.

8.5 Post-fire recovery

While runoff ratios and sediment concentrations continued to be substantially higher in burnt compared with unburnt areas at Upper Yarra, they had declined over the 18-month measurement period (Table 33) (Chapters 6 and 7). Recovery rates for runoff and erosion in other studies are highly variable ranging from two years (Prosser and Williams 1998; Sheridan *et al.* 2007) to 5-10 years (Benavides-Solorio and MacDonald 2005; Inbar *et al.* 1998). The reductions in runoff and erosion at Upper Yarra were associated with increases in surface vegetation cover from 0-16% immediately post-burn to 47-54% 18-months post-burn. Vegetation recovery is likely to have enabled higher infiltration and provided some protection for the soil surface from raindrops. A reduction in the availability of easily erodible ash and sediment may also have contributed to the declining sediment concentrations. After an initial decline in water repellency over the first six-months post-burn, fire-induced water repellency at Upper Yarra showed no evidence of recovery and continued to be greater in burnt areas during winter / spring for the remainder of the 18-month monitoring period.

Table 33: Results for hypotheses about post-fire recovery.

Hypothesis	Critical surface tension (Chapter 4)	Infiltrometer measurements (Chapter 5)	Rainfall simulations (Chapter 6)	Runoff samplers (Chapter 7)
Soil water repellency recovers fully within 18-months of prescribed burning (Hypothesis A2)	Rejected	---	---	---
Infiltration rates capacities recover fully within 18-months of prescribed burning (Hypothesis B2)	---	Not applicable[A]	Rejected	---
Runoff rates recover fully within 18-months of prescribed burning (Hypothesis C2)	---	---	Rejected	Rejected
Erosion rates recover fully within 18-months of prescribed burning (Hypothesis D2)	---	---	Rejected	Rejected

[A] Since prescribed burning had no effect on point-scale infiltration capacities, this hypothesis was no longer applicable.

In this discussion about post-fire recovery, it is important to recognise that the vast majority of runoff and sediment was generated from a few intense storms. For example, 71% of the sediment load from the high severity hillslope was measured on a single measurement date on the 27th November 2009 (Chapter 7). As discussed in Chapter 7, other studies also report that the majority of sediment is delivered from a few intense storms, which sometimes occur many months after burning (Inbar *et al.* 1998; Kunze and Stednick 2006; Lane *et al.* 2006). The debris flow example described in Chapter 2 demonstrated that large erosion events can occur many months after a burn provided there is an intense storm. At Upper Yarra no rainfall events had intensities that were comparable to the 44 mm h^{-1} event (I_{30}) measured on 27th November 2009. However, there were a few storms with relatively high intensities (I_{30} of approximately 20 mm h^{-1}) in March, November and December 2010, which showed much smaller runoff and erosion responses suggesting that susceptibility to these larger events was declining. Given the importance of intense storms, the 'window of disturbance' concept (Prosser and Williams 1998) should be framed in the context of storm magnitude (Figure 63). Windows of disturbance may be relatively short for high frequency, low magnitude rainfall events, but for the more intense storms they may be much longer.

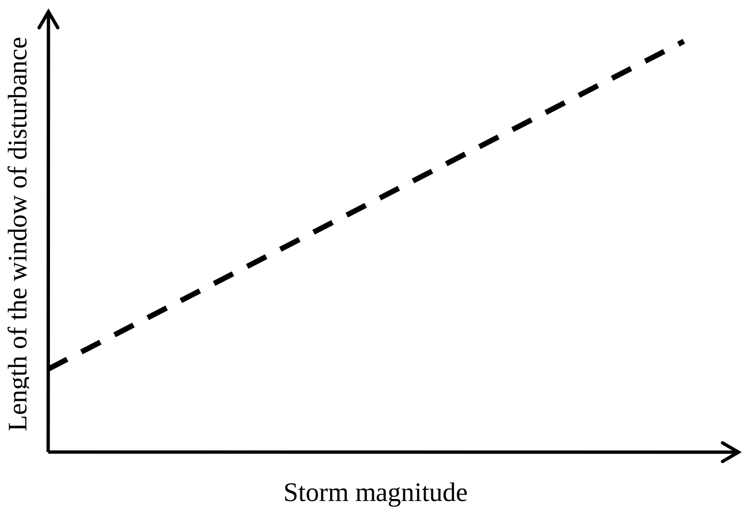


Figure 63: Hypothetical relationship between storm magnitude and the length of the 'window of disturbance'. For a given combination of site conditions, the length of the window of disturbance following burning is relative to the storm magnitude.

8.6 Extrapolating beyond the study constraints

8.6.1 Topographic variables

A number of topographic variables were held constant at Upper Yarra to enable the study to focus on the effects of fire severity and burn patchiness. Those factors include slope (22-25^{o}), aspect (north - westerly to north-easterly) and hillslope position (upper). This section briefly considers the potential effects of those factors on post-burn surface runoff and erosion, thus enabling the results to be extrapolated beyond the study constraints.

Generally, steeper slopes are associated with higher erosion rates as raindrops splash proportionally more soil particles downslope, flow velocities are higher and the volume of surface runoff is larger (Morgan 2005). Runoff rates are also likely to be higher on steeper slopes as surface depression storages are less and higher flow velocities mean there is less time for water to infiltrate. Consequently, runoff and erosion rates are likely to vary throughout a burnt catchment as a function of slope. Slope is also an important factor contributing to the likelihood of severe erosion (Nyman *et al.* 2011). Nyman *et al.* (2011) found that wildfire-induced debris flows occurred in catchments where 30-70% of the slopes were > 25^{o} and 3-48% were > 30^{o}. The debris flow example discussed in

Chapter 2 occurred in a relatively steep prescribed burnt catchment where 29% of the slopes were > 25^{o} and 14% was > 30^{o}.

In the southern hemisphere, the majority of runoff and sediment generated from a prescribed burnt catchment is likely to be generated from northerly aspects because southerly aspects are less likely to burn and have higher infiltration rates. Vegetation on southerly aspects is more difficult to burn during prescribed burns owing to its higher moisture content (Tolhurst and Cheney 1999), and therefore it more frequently remains unburnt (Bradstock *et al.* 2010; Penman *et al.* 2007). Furthermore, soils under forests types that occur on southerly aspects – e.g. wet or damp eucalypt forests – typically exhibit high infiltration capacities due to their depth and better structure (Ashton and Attiwill 1994; Lane *et al.* 2004). Large numbers of macropores are thought to reduce the connectivity of runoff, even under water repellent conditions (Nyman *et al.* 2010a; Sheridan *et al.* 2007).

Lower slope positions and riparian zones have some similarities to southerly aspects in that they often remain unburnt during a prescribed burn (Bradstock *et al.* 2010; Penman *et al.* 2007). For example, Smith *et al.* (2010) reported minimal burning on the lower slopes and in the riparian zones following a prescribed burn in dry to damp eucalypt forest in north-eastern Victoria. If unburnt patches on the lower slopes are as effective at reducing runoff and erosion from upslope burnt areas as unburnt patches on the upper slopes, then the extent of burning in these lower slope regions may be an important determinant of runoff and erosion connectivity following burning, and subsequent water quality impacts. Further measurements are required in these lower parts of the catchment, particularly under saturated conditions, to determine the effectiveness of unburnt patches in these positions at reducing runoff and erosion connectivity.

8.6.2 **Similarities and differences between study sites**

In this study, some measurements (soil temperature, water repellency, infiltration and surface cover) were conducted at all three study sites. The sites were similar in several respects (aspect, slope, broad vegetation classification) but also differed in other respects (geographic location, geology, soil texture, surface fuel load and climatic conditions during the study period). The primary intent of conducting measurements at three sites was to increase the likelihood that a desirable burn outcome would be achieved in one of the sites (discussed in Chapter 3). An additional benefit was that insights were gained into the broader applicability of the Upper Yarra results.

The effects of burning on soil hydrologic properties varied between the sites, possibly reflecting differences in the extent of soil heating during the burn. Mt Cole was similar to Upper Yarra, in that water repellency increased following burning (Chapter 4) and this did not affect point-scale infiltration capacities (Chapter 5). At Big Ben, burning had no effect on water repellency or infiltration capacity. This is probably a reflection of the types of surface fuel (predominately grasses) and subsequent lower soil temperatures reached during the burn at Big Ben compared with the other sites (despite fire severity appearing similar to the other sites). Interestingly, this result suggests that fire severities of similar visual appearance in different locations do not necessarily affect soil hydrologic properties in the same way.

Importantly, all three sites exhibited pre-existing water repellency. Similarly, other post-fire studies have reported pre-existing water repellency in unburnt eucalypt forests (Doerr *et al.* 2004; Ronan 1986; Sheridan *et al.* 2007). The implication of this is that fire-induced water repellency is less important as a determinant of post-fire runoff and erosion (as discussed previously) than where it may only be present following burning.

Erosion rates were only measured at Upper Yarra, but observations suggested that more erosion was occurring at Mt Cole. In particular, there was evidence of both rill and interrill erosion at Mt Cole but only interrill erosion at Upper Yarra and Big Ben. Higher erosion rates at Mt Cole could be a function of several different factors including:

- More rainfall sooner after the burn. Burning was succeeded immediately by a wet period at Mt Cole whereas the months following burning at Upper Yarra and Big Ben were relatively dry (Chapter 3)
- Fewer unburnt patches. There were fewer unburnt patches at Mt Cole (0% of the sampling points were unburnt in low severity at Mt Cole versus 28-35% at Upper Yarra and Big Ben – Chapter 3) and hence probably less trapping of runoff and erosion on the hillslope
- Lower storage capacities in surface depressions and holes. These were only surveyed at Upper Yarra but are likely to have been less influential at Mt Cole as surface depressions are thought to have larger storage capacities (1.6-2.3 times larger) in clay soils (Upper Yarra) compared with sandy soils (Mt Cole) (Morgan 2005).

8.6.3 Scaling up from hillslopes to catchments

Runoff and erosion rates were minimal from the unburnt hillslope at Upper Yarra with an average runoff ratio of 0.01% and a cumulative sediment load of 1.5 g m^{-1} or 0.00011 t ha^{-1} y^{-1} (assuming a contributing hillslope length of 100 m). Other studies have also reported low runoff and erosion rates from unburnt eucalypt forests (Bren and Turner 1979; Prosser and Williams 1998; Ronan 1986), as discussed in Chapter 7. Such low rates of hillslope runoff and erosion suggest that unburnt hillslopes contribute little to instream suspended sediment loads (TSS) at the catchment-scale. Few studies report catchment-scale TSS loads for undisturbed eucalypt forests (Table 34). Of the catchments listed in Table 34, the Ella Creek catchment (Hopmans and Bren 2007) – with its mixed-species eucalypt forest – probably most resembles the Upper Yarra study site. Assuming the instream TSS load at Upper Yarra was similar to that of Ella Creek (i.e. 0.0095 t ha^{-1} y^{-1}), then the hillslope contribution to this TSS load (i.e. 0.00011 t ha^{-1} y^{-1}) would be approximately 1.2%.

Table 34: Total suspended sediment loads for undisturbed forest catchments in Victoria

Location	Vegetation type	Sediment load (t ha-1 y-1)	Author
Upper section of the Tyers River catchment (13,451 ha) on the southern face of Mt Baw Baw , Victoria	Ash eucalypt forest (wet)	0.085 Sampling over one year	Sheridan and Noske (2007)
Ella Creek catchment (113 ha), a tributary to the Buffalo river, Victoria.	Mixed-species eucalypt forest (dry)	0.0095 Weekly sampling over six years plus storm events	Hopmans and Bren (2007)
Stony Creek (75 ha), a tributary to the Latrobe River, Victoria	Ash eucalypt forest (wet)	0.024 Sampling over five months	Lane and Sheridan (2002)
Sub-catchment (25 ha) of Myrtle Creek in the Maroondah catchment, Victoria	Ash eucalypt forest (wet)	0.076 Sampling over 10 years	Grayson et al. (1993)

Total sediment loads from the high severity (2058 g m^{-1} or 0.15 t ha^{-1} y^{-1}) and low severity (1671 g m^{-1} or 0.13 t ha^{-1} y^{-1}) hillslopes at Upper Yarra were approximately three orders of magnitude larger than from the unburnt hillslope (1.5 g m^{-1} or 0.00011 t ha^{-1} y^{-1}). Other studies also report large increases in runoff and erosion in burnt areas. For example, Prosser and Williams (1998) found the sediment load at the hillslope-scale increased by nearly two orders of magnitude following burning in the Blue Mountains (NSW, Australia), while Inbar *et al.* (1998) found the sediment load at the hillslope-scale increased by approximately two to four orders of magnitude following burning at Mt Carmel in Israel. The significance of those increases at the catchment-scale depends on the relative contribution of hillslope runoff and erosion to instream TSS loads. By using the Ella Creek catchment as an example (Hopmans and Bren 2007), the effect of burning on catchment-scale TSS loads can be estimated. If burning within the Ella catchment resulted in similar amounts of surface runoff and erosion to burning at Upper Yarra, then burning the entire catchment could increase the instream TSS load by approximately three orders of magnitude from 0.0095 t ha^{-1} y^{-1} to approximately 14.1-17.4 t ha^{-1} y^{-1}. Such large increases could have water quality implications. Additionally instream erosion rates may increase due to greater stream power and the loss of riparian vegetation.

Despite this potential for substantial increases in TSS at the catchment-scale, prescribed burns are usually reported to have minimal impacts on water quality at the catchment-scale (Table 1 in Chapter 2) (Scott 1993; Smith *et al.* 2010; Townsend and Douglas 2000). The results of this study suggest that those minimal impacts at the catchment scale may be a function of burn patchiness. This study has shown that unburnt patches are highly effective at reducing runoff and erosion connectivity (Chapter 7) and are potentially the cause of minimal erosion and water quality impacts following prescribed burning at the catchment-scale, despite larger impacts at the plot-scale.

8.7 Management implications

The results of this study highlight the importance of unburnt patches in reducing runoff and erosion connectivity within a prescribed burn; in contrast fire severity had less influence on runoff and erosion rates. The effectiveness of unburnt patches at reducing runoff and erosion connectivity across a hillslope depends on the proportion of burnt relative to unburnt area and the density (or size) of the burnt/unburnt patches. In addition to those factors, the proximity of unburnt patches to streams is an important determinant of runoff and erosion connectivity between burnt patches and streams (and thus the potential for water quality impacts). Although fire severity was less important to runoff and erosion rates in this study, patchy burn outcomes are more likely to be achieved if the severity of the burn is lower.

The hypothetical model in Figure 64 illustrates how the proportion of burnt/unburnt area and patch density may affect the potential for runoff and erosion connectivity at hillslope- to catchment-scales. As discussed throughout this thesis, hydrologic connectivity also depends on other factors not shown in this diagram (e.g. rainfall intensity and slope gradient). By minimising runoff and erosion connectivity following a burn, there is less potential for water quality impacts and greater potential for rapid vegetation regeneration as fewer soil-stored seeds and nutrients are eroded from the hillslope. The hypothetical model (Figure 64) predicts that the potential for runoff and erosion connectivity declines as the proportion of unburnt area increases and patch density increases (patches become smaller). For example, if 50% of the area is unburnt and patch diameters are 10 m then the site is likely to have a moderate potential for runoff/erosion connectivity, whereas if 20% of the area is unburnt and patch diameters are 30 m then the site is likely to have high potential for runoff/erosion connectivity. The rationale behind these predictions is based on the outcomes of this study and other studies reviewed in Chapter 2. Unburnt patches generate little runoff and erosion and are highly effective at reducing runoff and erosion from upslope burnt areas (as demonstrated in Chapters 6 and 7). Therefore, a burn with a high proportion of unburnt area has less capacity to produce runoff and erosion. Many small patches of vegetation hinder runoff and erosion connectivity more effectively than a few large patches as the accumulation of runoff and erosion in the bare patches is more frequently intercepted by a vegetated patch; as reported by Bautista *et al.* (2007), and Boer and Puigdefábregas (2005), and as illustrated in Figure 9. Therefore, a burn with a fine-grained mosaic of burnt/unburnt patches is likely to have a lower potential for runoff and erosion connectivity than one with a coarse-grained mosaic of burnt/unburnt patches. The management implication of this is that prescribed burns should aim to achieve a fine-grained mosaic of burnt and unburnt patches (5-10 m diameter), with > 50% of the area unburnt.

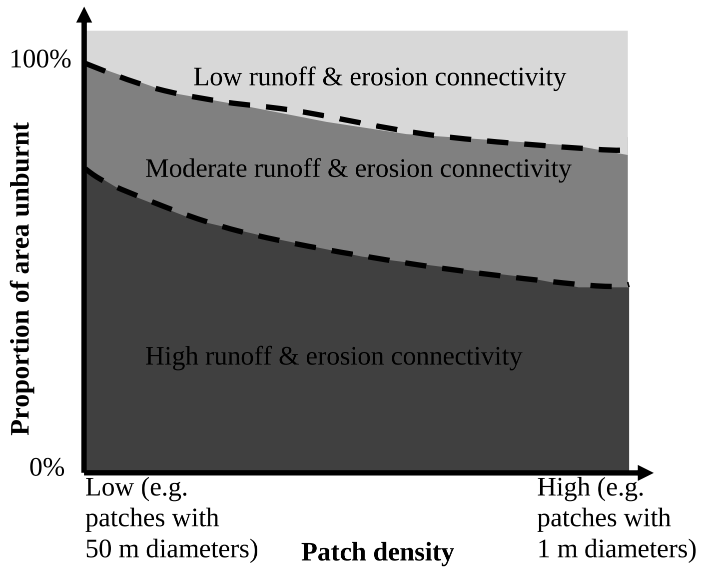


Figure 64: Hypothetical diagram showing how the proportion of unburnt area and patch density are likely to affect the runoff and erosion connectivity across a hillslope or catchment. An assumption is that patches are randomly arranged throughout the burn.

Of course, from a water quality perspective, the spatial arrangement of patches is also an important factor to consider. Figure 65 illustrates the potential significance of different patch arrangements on the amount of burnt area connecting to the bottom of a hillslope and thus potentially contributing runoff and erosion to a stream and causing water quality issues. For each scenario 80% of the hillslope is burnt and 20% is unburnt. The unburnt patches are wide enough to reduce runoff and erosion from upslope burnt areas by 100% under moderate rainfall conditions. Based on the outcomes of this study (Chapter 7), that would mean that they are 5-10 m wide (not 1 m wide). The percentage values represent the *potential* burnt area connected to the stream. The *actual* burnt area contributing runoff and erosion to the stream is likely to be less than the potential area due to interception by obstacles or deposition when the sediment weight exceeds the energy of the overland flow. It will also vary as a function of rainfall intensity, slope and other site characteristics. The diagram shows that unburnt patches anywhere on the hillslope reduce the potential burnt area connecting to the stream to some extent with those towards the bottom of the hillslope having the greatest effect. The management implication of this is that unburnt streamside buffers > 10 m wide should be retained within prescribed burns to minimise the potential for runoff and erosion connectivity between burnt areas and the stream.

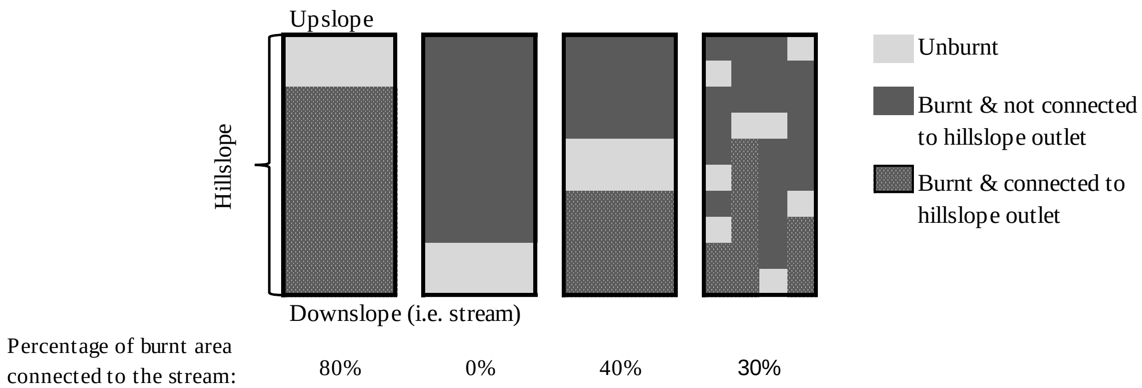


Figure 65: Percentage of burnt area *potentially* connected to a stream for different unburnt patch arrangements. For each hillslope 80% is burnt and 20% is unburnt. Unburnt patches are wide enough reduce runoff and erosion from upslope burnt areas by 100%. An assumption is that the hillslope is planar.

Achieving patchy burn outcomes and unburnt streamside zones is feasible from a burn operational perspective and is likely to be compatible with other prescribed burning objectives (e.g. reducing the spread of wildfire) in some areas but not others. It is possible for burn practitioners to achieve a mosaic of burnt and unburnt patches throughout their prescribed burns by using a range of techniques (Tolhurst and Cheney 1999) including:

- spot ignition patterns (rather than strip ignition patterns) to minimise the fire intensity
- igniting from the top (rather than the bottom) of hillslope to promote backing fire, which is less intense than head fire
- choosing weather conditions conducive to less intense fire behaviour. For example, days with light wind, cooler temperatures, higher humidity, and higher fuel moisture contents. Of course the conditions still need to be sufficiently dry and warm for the burn to occur.
- burning when the fuels on the upper slopes are sufficiently drier than those on the lower slopes so that the burn self-extinguishes when it reaches a gully
- burning when there are moisture differentials between different vegetation types and aspects, so that the burn self-extinguishes in patches throughout the burn unit.

For many prescribed burns achieving a mosaic of burnt and unburnt patches is compatible with the broader objective of the burn. For example, in Victoria (Australia) many burns are designed to achieve a mosaic of burnt and unburnt areas, with 50% of the area remaining unburnt (Department of Sustainability and Environment 2006). These burns usually occur in remote locations where the effectiveness of the burn at reducing the spread of wildfire can be compromised to some extent to also enable a more ecologically desirable burn outcome with a mosaic of habitat types and vegetation age-classes retained. Closer to human settlements, wildfire mitigation becomes more important and prescribed burns aim to burn 70-90% of the area. Such objectives are less compatible with the management recommendations of the present study, but even within these burns it may be possible to retain unburnt streamside buffers.

While burn patchiness reduces erosion susceptibility, it may not be possible to eliminate severe erosion during intense storms. The debris flow example discussed in Chapter 2 illustrates this point. This burn was patchy and there had been significant recovery post-fire; yet a debris flow still occurred. There are probably some site characteristics that make particular areas more susceptible to post-fire debris flows – e.g. slope, hillslope convergence, aspect and slope type (Nyman, 2011). More research is required to quantify the significance of each of those factors, their frequency across landscapes and the feasibility of not carrying out prescribed burns in those areas.

8.8 Overall conclusions

The overall aim of this thesis was to quantify the effects of prescribed burning on soil hydrologic properties, surface runoff and erosion in dry eucalypt forests. This was done by examining the effects of fire severity and burn patchiness – two potentially important characteristics of the fire regime – on point, plot and hillslope-scale properties and process in a prescribed burnt catchment. The general conclusions were that:

- Prescribed burning can increase soil water repellency, presumably as a result of soil heating, but the effects of those increases on infiltration and runoff are negligible relative to the effects of pre-existing soil water repellency.
- Runoff and erosion rates may be elevated in burnt areas relative to unburnt areas. For example, cumulative hillslope runoff volumes were found to be approximately two orders of magnitude higher and sediment loads were approximately three orders of magnitude higher on burnt than on unburnt hillslopes.
- The loss of surface vegetation cover is likely to be the primary driver for elevated runoff and erosion in burnt areas. It causes lower interception rates, greater raindrop impact (and potentially soil sealing), less surface roughness and shallower ponded depths (potentially enhancing the effects of soil water repellency).
- Infrequent, intense storms (i.e. storms with average recurrence intervals > 10 years) cause the vast majority of runoff and erosion.
- The post-fire window of disturbance or susceptibility of burnt areas to erosion varies depending on the storm intensity; where particularly intense storms occur post-fire the window of disturbance is likely to be longer.
- There is relatively little difference in runoff and erosion rates between low and high fire severity areas, presumably because the amount of surface vegetation is similar for both severities.
- Unburnt patches effectively intercept the downslope movement of water and sediment; their effectiveness varies as a function of patch width and rainfall intensity.

- Despite considerably elevated runoff and erosion rates in burnt areas at plot and hillslope-scales, prescribed burns are unlikely to cause substantial erosion (or have major water quality impacts) under moderate rainfall conditions provided there are unburnt patches throughout the burnt area, which act as runoff and sediment traps.
- During very intense storms, severe erosion may occur (e.g. debris flows) following prescribed burning, as demonstrated in Chapter 2 for a catchment in north-eastern Victoria.
- The effects of prescribed burning may persist for longer than 18-months.

The management implications of these results is that unburnt patches within a prescribed burn are extremely important for minimising runoff, erosion and water quality impacts. The severity of a prescribed burn from an erosion perspective is a function of the extent, size and arrangement of unburnt patches, rather than the fire severity of the burn. Therefore, fire managers should aim to achieve a mosaic of burnt and unburnt patches throughout their prescribed burns, with particular focus on maintaining unburnt buffer zones near streams to help prevent sediment reaching channels.

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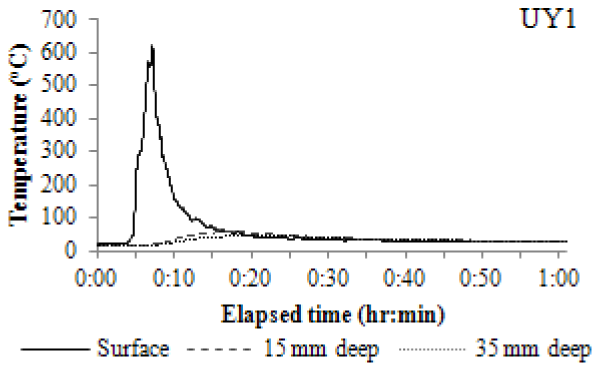
10. Appendix

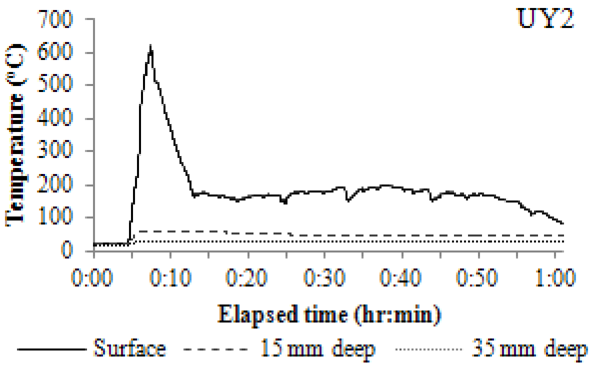
10.1 Thermocouple data

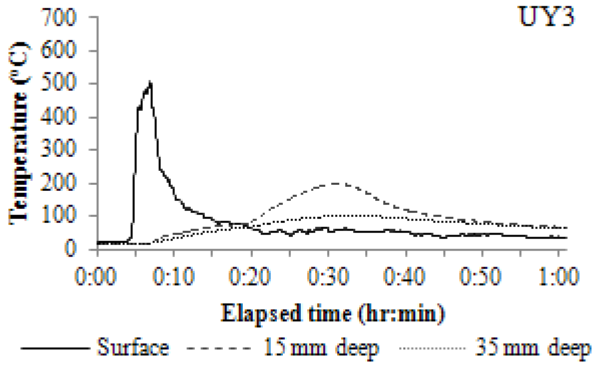
Appendix 1: Maximum temperatures measured with thermocouples at the Upper Yarra and the duration of heating above 175 °C and 280 °C – i.e. temperature thresholds associated with changes to soil water repellency (DeBano 2000).

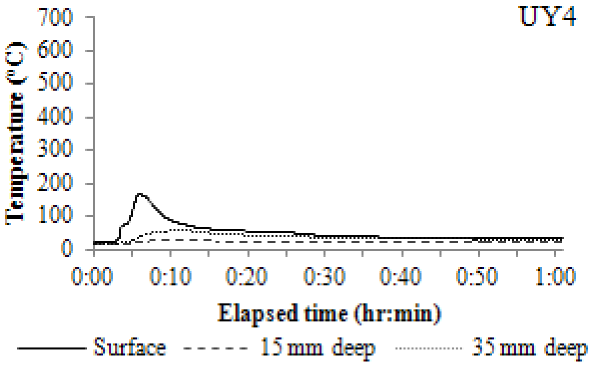
Fire severity	Description	Soil depth (mm)	Maximum temp. (°C)	Heating duration (min) >175 °C	Heating duration (min) >280 °C	Location
High severity	Surface fuels (litter) burnt; Understorey burnt; Canopy burnt	0	622	4.9	3.4	UY1 (Block 1)
		15	54	0	0	
		35	43	0	0	
		0	621	24.3	5.3	UY2 (Block 1)
		15	58	0	0	
		35	28	0	0	
		0	510	5.2	3.1	UY3 (Block 1)
		15	194	0.1	0	
		35	98	0	0	
		0	168	0	0	UY4 (Block 1)
		15	24	0	0	
		35	54	0	0	
High severity	Surface fuels (litter) burnt; Understorey burnt; Canopy scorched	0	362	2.4	1.1	UY5 (Block 1)
		15	46	0	0	
		35	22	0	0	
		1	39	0	0	

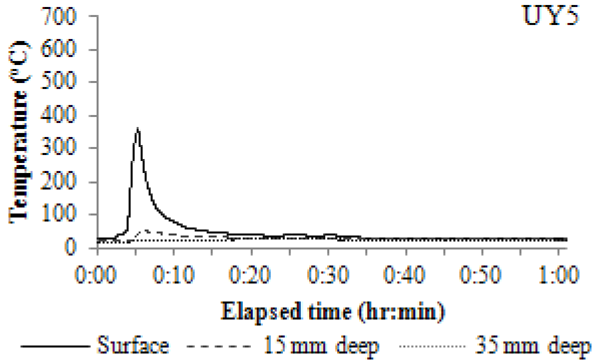
Appendix 2: Time-series charts for soil heating at Upper Yarra.







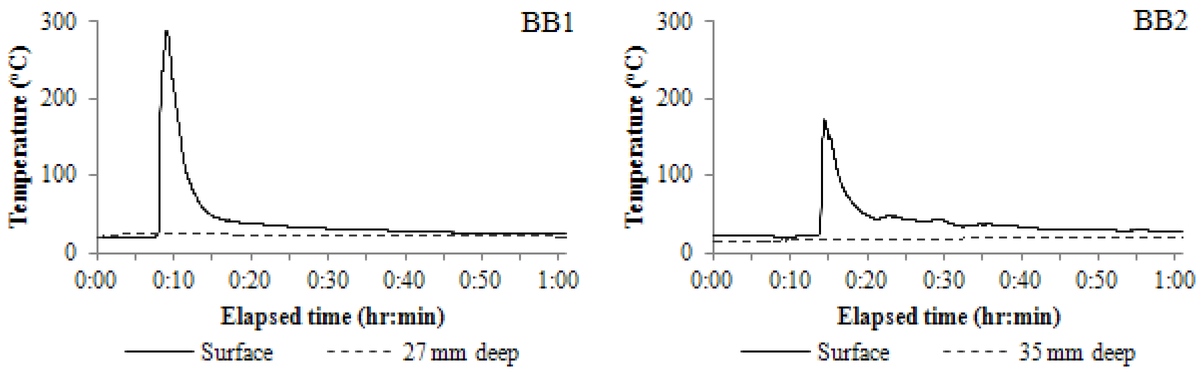




Appendix 3: Maximum temperatures measured with thermocouples at Big Ben and the duration of heating above 175 °C and 280 °C – i.e. temperature thresholds associated with changes to soil water repellency (DeBano 2000).

Fire severity	Description	Soil depth (mm)	Maximum temp. (°C)	Heating duration (min) >175 °C	Heating duration (min) >280 °C	Location
Low severity	Surface fuels (grass) burnt or charred	0	288	2.3	0.4	BB1 (Block 1)
		27	23	0	0	
	No understorey	0	172	0	0	BB2 (Block 1)
	Canopy unburnt	35	18	0	0	

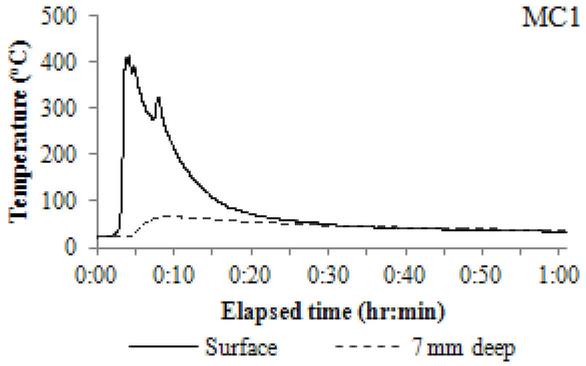
Appendix 4: Time-series charts for soil heating at Big Ben.

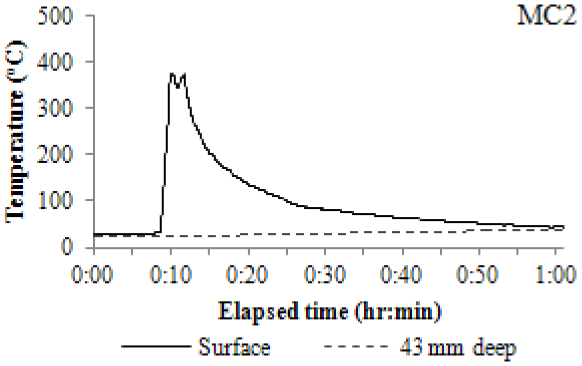


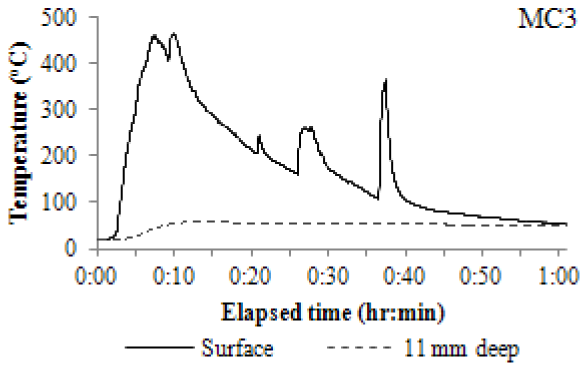
Appendix 5: Maximum temperatures measured with thermocouples at Mt Cole and the duration of heating above 175 °C and 280 °C – i.e. temperature thresholds associated with changes to soil water repellency (DeBano 2000).

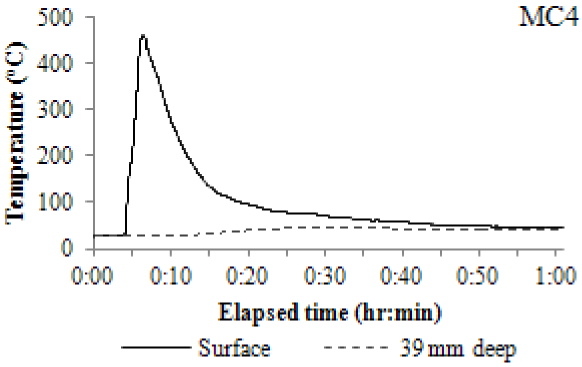
Fire severity	Description	Soil depth (mm)	Maximum temp. (°C)	Heating duration (min) >175 °C	Heating duration (min) >280 °C	Location
Low severity	Surface fuels (grass) burnt or charred; No understorey; Canopy unburnt	0	415	8.0	4.7	MC1 (Block 1)
		7	64	0	0	
		0	377	7.4	3.1	MC2 (Block 1)
		43	34	0	0	
		0	466	26.4	11.6	MC3 (Block 1)
		11	56	0	0	
		0	464	8.3	4.5	MC4 (Block 1)
		39	43	0	0	
		0	419	28.4	2.0	MC5 (Block 1)
		4	251	4.25		
Low severity	Surface fuels (litter) burnt; Understorey scorched; Canopy unburnt	0	120	0	0	MC6 (Block 2)
		40	45	0	0	
		0	341	9.3	5.1	MC7 (Block 2)
		10	68	0	0	
Low severity	Surface fuels (litter) burnt; Understorey unburnt; Canopy unburnt	0	300	6.0	1.0	MC8 (Block 2)
		20	89	0	0	
		0	375	8.3	4.6	MC9 (Block 2)
		2	57	0	0	
		0	274	0.6	0	MC10 (Block 2)
		1	39	0	0	

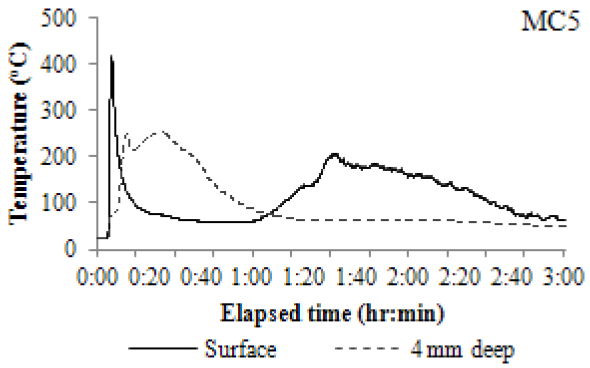
Appendix 6: Time-series charts for soil heating at Mt Cole (Block 1).



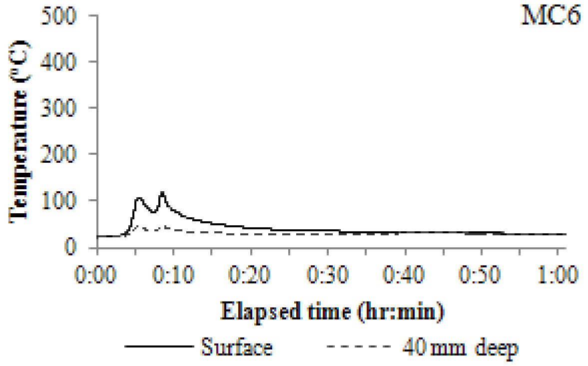


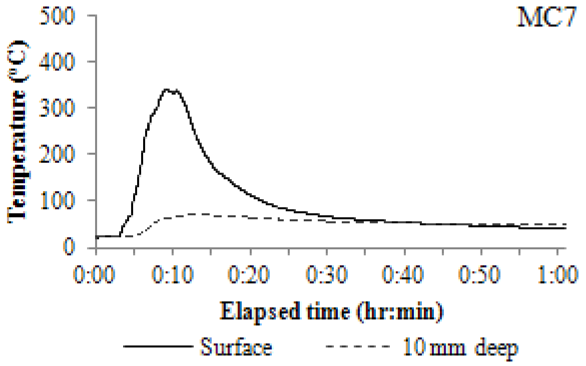


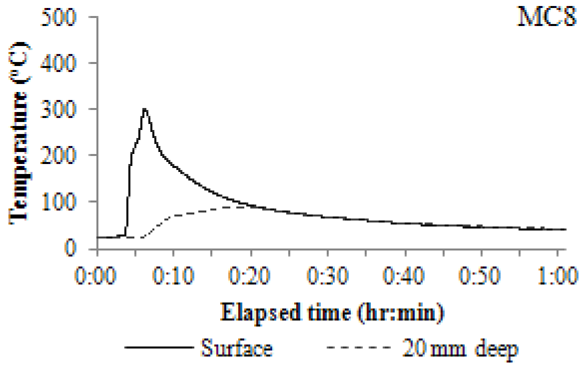


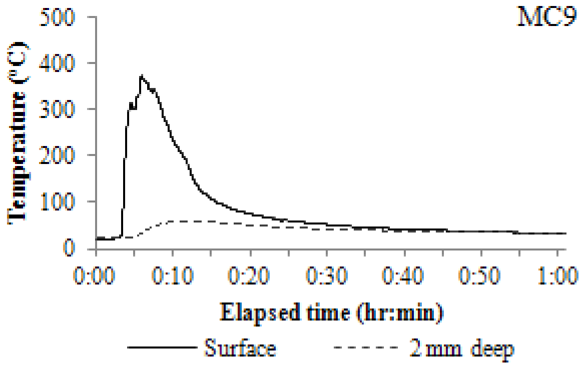


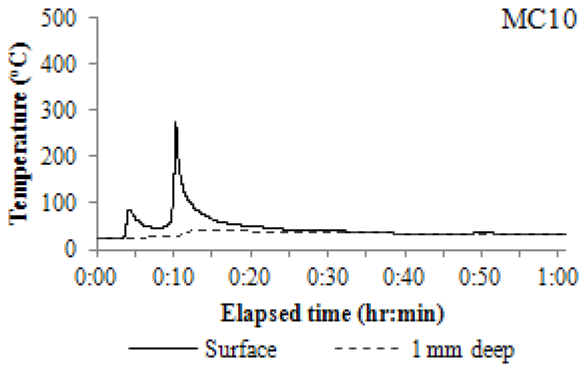
Appendix 7: Time-series charts for soil heating at Mt Cole (Block 2).











10.2 Summary statistics for water repellency measurements

Appendix 8: Soil water repellency statistics for the Upper Yarra (mN m^{-1})

	Autumn 2009			Spring 2009			Autumn 2010			Spring 2010		
	Unburnt	**Low**	**High**	**Unburnt**	**Low**	**High**	**Unburnt**	**Low**	**High**	**Unburnt**	**Low**	**High**
Number	29	47	7	12	44	16	20	27	14	24	43	24
Skewness	-0.2	1.0	-0.2	1.1	-1.6	-0.3	-0.4	-1.1	-0.7	1.1	-0.8	-0.6
Minimum	32	32	32	72	32	32	32	32	33	72	32	32
Q1	41	33	33	72	63	32	37	43	44	72	36	32
Median	52	36	36	72	72	72	67	72	72	72	72	72
Q3	72	57	37	72	72	72	72	72	72	72	72	72
Maximum	72	72	38	72	72	72	72	72	72	72	72	72

Appendix 9: Soil water repellency statistics for Big Ben (mN m^{-1})

	Autumn 2009			Spring 2009		
	Unburnt	**Low**	**High**	**Unburnt**	**Low**	**High**
Number	10	39	7	19	35	8
Skewness	-1.7	-1.3	-1.9	1.1	-2.4	-1.2
Minimum	39	32	38	72	32	32
Q1	65	60	64	72	72	53
Median	72	72	72	72	72	72
Q3	72	72	72	72	72	72
Maximum	72	72	72	72	72	72

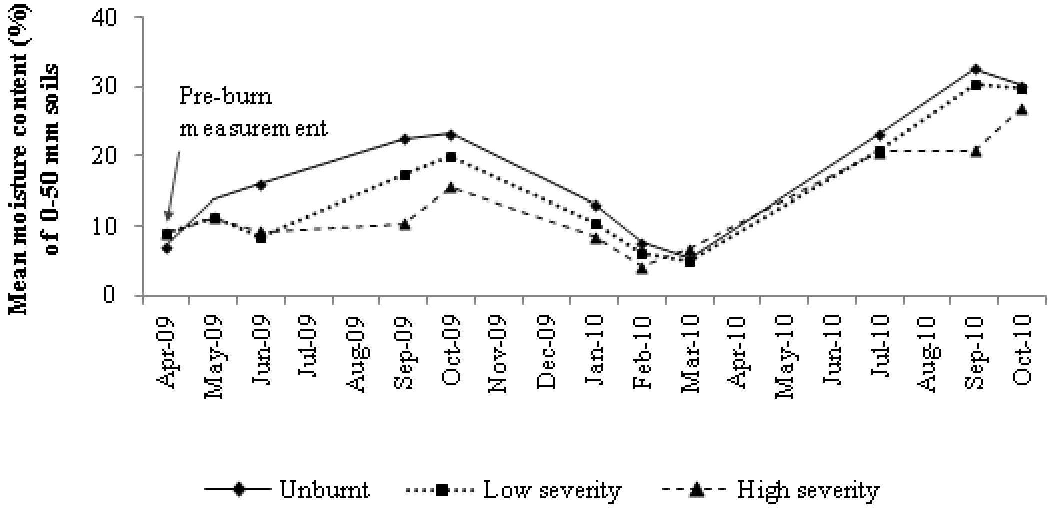
Appendix 10: Soil water repellency statistics for Mt Cole (CST: mN m^{-1})

	Autumn 2010		Spring 2010	
	Unburnt	**Low**	**Unburnt**	**Low**
Number	16	48	16	48
Skewness	-0.01	2.1	-1.6	1.3
Minimum	32	32	32	32
Q1	32	32	68	33
Median	53	32	72	36
Q3	72	33	72	45
Maximum	72	72	72	72

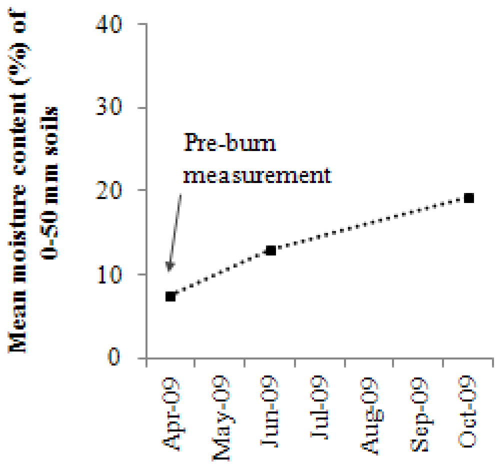
10.3 Soil moisture data

Appendix 11: Mean soil moisture contents (%) for surface and sub-surface soils in different fire severities

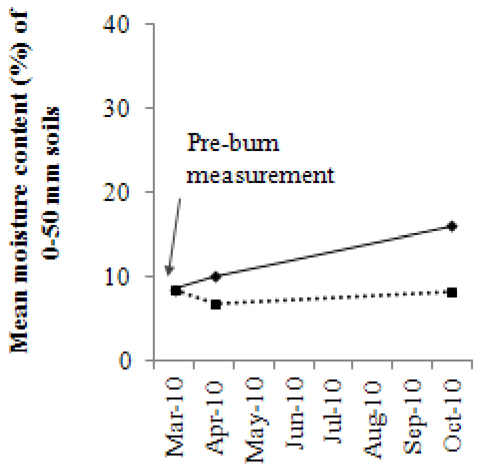
(a) Upper Yarra



(b) Big Ben



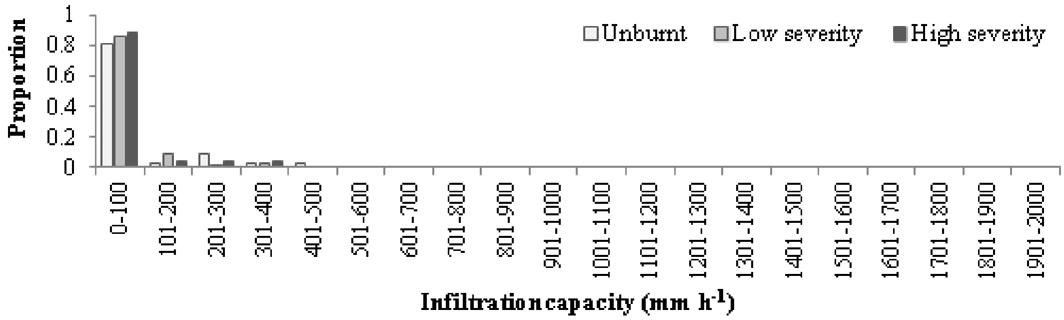
(c) Mt Cole



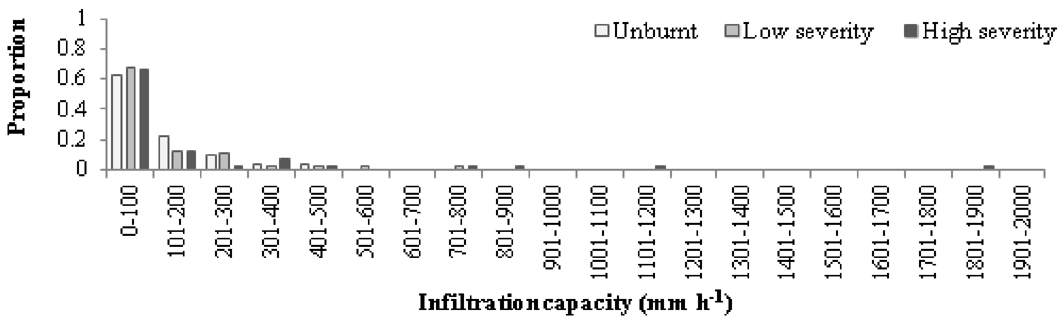
10.4 Frequency charts for infiltration capacity

Appendix 12: Frequency charts for ponded infiltrometer measurements in unburnt, low severity and high severity plots at Upper Yarra (autumn and spring 2009 and 2010), Big Ben (autumn and spring 2009) and Mt Cole (autumn and spring 2010). Classes on the horizontal axes are 100 mm h^{-1}.

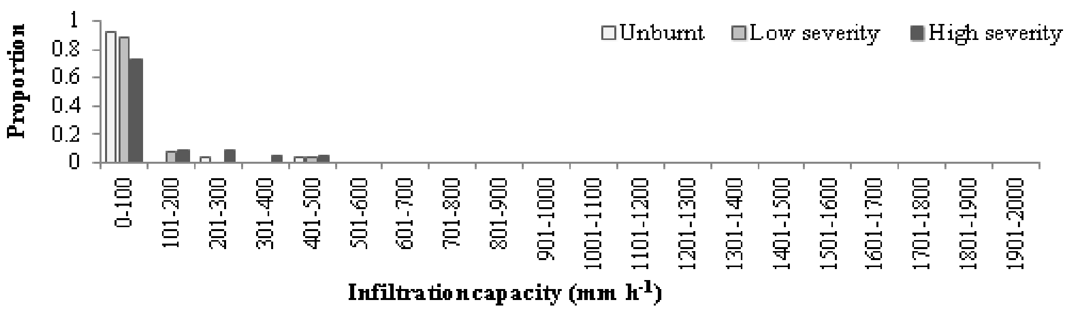
(a) Upper Yarra – Autumn 2009



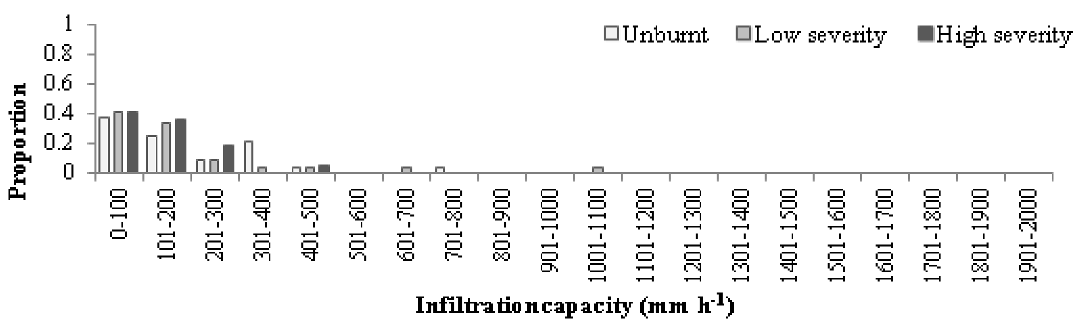
(b) Upper Yarra – Spring 2009



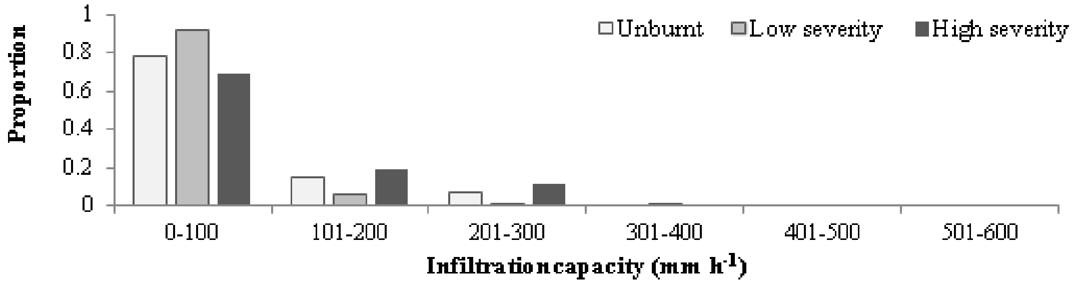
(c) Upper Yarra – Autumn 2010



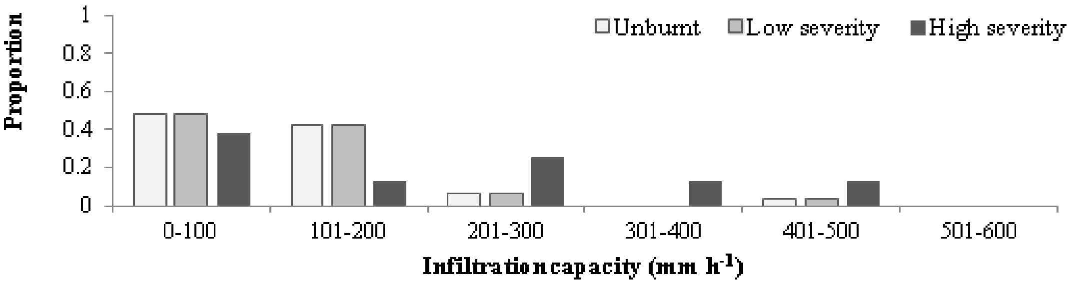
(d) Upper Yarra – Spring 2010



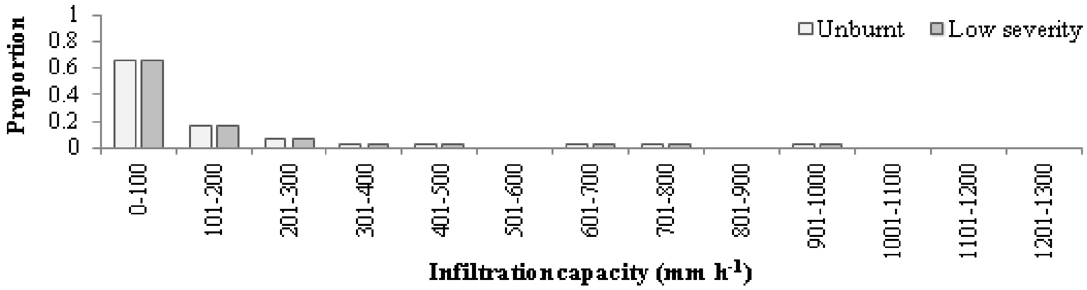
(e) Big Ben – Autumn 2009



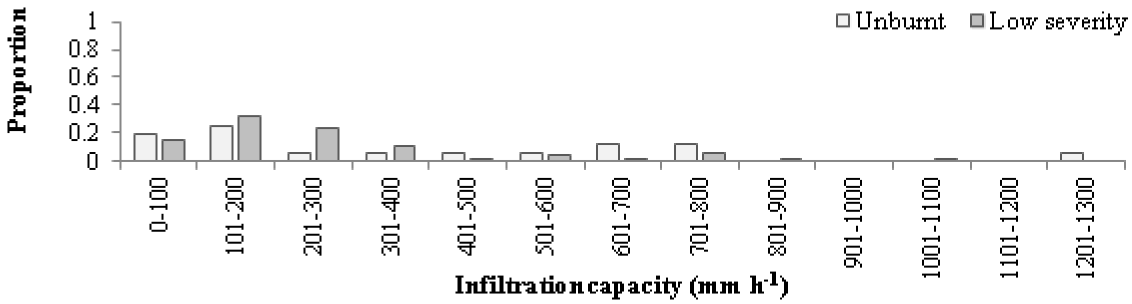
(f) Big Ben – Spring 2009



(h) Mt Cole – Autumn 2010



(i) Mt Cole – Spring 2010



10.5 Summary statistics for the infiltrometer measurements

Appendix 13: Summary statistics for steady-state infiltration capacities (mm h^{-1}) measured with ponded infiltrometers.

Upper Yarra

	Autumn 2009			Spring 2009			Autumn 2010			Spring 2010		
	Unburnt	Low	High	Unburnt	Low	High	Unburnt	Low	High	Unburnt	Low	High
N	33	65	26	36	47	41	24	25	22	24	24	24
Median	0	0	0	64	62	62	24	47	24	154	119	141
Minimum	0	0	0	0	0	0	0	0	0	12	24	12
Maximum	493	322	332	403	711	1840	403	450	450	735	1095	403
Mean	61	29	30	104	107	190	52	70	88	202	198	136
Standard deviation	123	72	83	104	147	356	87	90	121	168	238	97
Coefficient of variation (%)	201	248	277	100	138	187	167	129	138	83	120	71

Big Ben

	Autumn 2009			Spring 2009		
	Unburnt	Low	High	Unburnt	Low	High
N	14	70	26	18	31	8
Median	0	0	0	107	119	178
Minimum	0	0	0	24	0	47
Maximum	237	343	294	332	462	474
Mean	56	30	73	121	118	194
Standard deviation	82	66	98	80	90	149
Coefficient of variation (%)	146	220	134	66	76	77

Mt Cole

	Autumn 2010		Spring 2010	
	Unburnt	Low	Unburnt	Low
N	33	40	16	48
Median	47	71	273	25
Minimum	0	0	47	0
Maximum	522	925	1233	1090
Mean	108	146	403	277
Standard deviation	158	208	341	241
Coefficient of variation (%)	146	142	85	87

Appendix 14: Summary statistics for steady-state infiltration capacities (mm h^{-1}) measured with tension infiltrometers.

Upper Yarra

	Spring 2009			Autumn 2010			Spring 2010		
	Unburnt	Low	High	Unburnt	Low	High	Unburnt	Low	High
N	32	47	41	24	25	22	24	24	24
Median	20	8	13	7	39	20	19	19	19
Minimum	0	0	0	0	0	0	6	6	4
Maximum	71	489	237	79	711	237	75	38	38
Mean	28	24	41	14	74	32	25	22	21
Standard deviation	21	71	56	19	141	51	22	11	10
Coefficient of variation (%)	75	296	137	136	190	159	88	50	500

Big Ben

	Spring 2009		
	Unburnt	Low	High
N	18	31	8
Median	38	38	75
Minimum	3	0	15
Maximum	78	75	75
Mean	39	33	56
Standard deviation	20	22	27
Coefficient of variation (%)	51	67	48

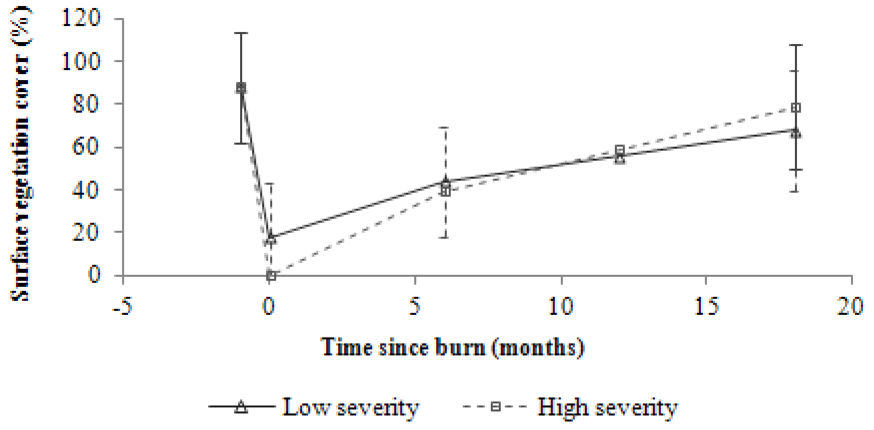
Mt Cole

	Autumn 2010		Spring 2010	
	Unburnt	Low	Unburnt	Low
N	25	48	25	48
Median	0	6	19	19
Minimum	0	0	0	0
Maximum	79	79	75	151
Mean	9	11	24	24
Standard deviation	18	18	17	26
Coefficient of variation (%)	200	163	71	108

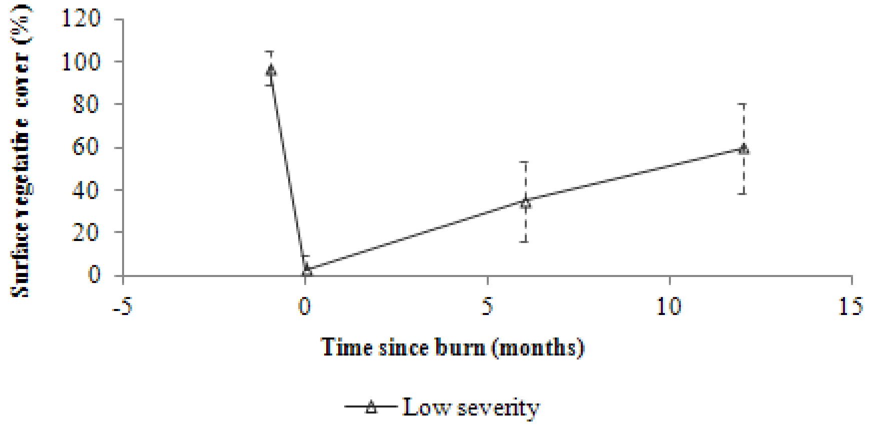
10.6 Surface cover for sample points at Big Ben and Mt Cole

Appendix 15: Mean values for surface vegetative cover as a function of time since fire for low and high severity areas at (a) Big Ben and (b) Mt Cole. Error bars denote the standard deviations.

(a) Big Ben



(b) Mt Cole



10.7 Summary statistics for runoff samplers

Appendix 16: Summary statistics for erosion: mean sediment concentration in runoff (C) (g L^{-1}), standard deviation for the mean sediment concentration (g L^{-1}), sediment load per metre width of hillslope (S) (g m^{-1}) and the outcome of T-tests comparing mean sediment concentrations between treatments for each measurement date (the same letter is applied to treatments with no statistically significant difference, $p > 0.05$). Blank cells indicate that there was insufficient runoff to measure the sediment concentration.

		28-Aug-09	02-Sep-09	10-Sep-09	18-Sep-09	22-Sep-09	25-Sep-09	30-Sep-09	13-Oct-09	20-Oct-09	27-Nov-09	01-Dec-09	12-Dec-09	06-Jan-10	25-Jan-10	10-Feb-10	16-Feb-10	21-Mar-10	09-Apr-10	29-Apr-10	12-Jul-10	26-Jul-10	07-Sep-10	19-Oct-10	02-Nov-10	Cumulative total (*SO*)
High severity	**Mean (*C*)**	0.69	0.05	0.01	0.05	0.35	0.03	0.29	0.42	0.98	7.40	2.60	1.89	0.46	0.53	0.99	1.02	1.40	1.79	0.29	0.17	0.41	0.18	0.31	0.27	
	St Dev	0.52	0.08	0.03	0.09	0.58	0.06	0.58	0.75	1.42	4.19	1.91	1.26	0.32	0.77	0.72	0.81	0.94	1.27	0.31	0.20	0.24	0.24	0.41	0.33	
	Load (*S*)	29.1	1	0	0	4	0	40	4	36.5	1454	12.9	113	9	23.5	1	7	184	94	16	4	1	6	9	10	2058
	T-Test	a	a	a	a	a	a	a	a	a	a	a	a	a	ab	a	a	a	a	a	a	a	a	a	a	
Low severity	**Mean (*C*)**	1.23	0.11	0.06	0.07	0.23	0.25	0.09	0.25	1.69	4.07	0	1.32	0.27	0.38		0.49	0.55	0.51	0.16	0.29	0.55	0.21	0.25	0.35	
	St Dev	1.26	0.12	0.13	0.10	0.16	0.35	0.10	0.30	1.25	2.50	0	0.61	0.18	0.28		0.79	0.32	0.37	0.18	0.26	0.57	0.16	0.34	0.51	
	Load (*S*)	70.9	1.1	1.7	0.5	2.6	0.5	11.8	1.6	43.3	1267	0.0	106.4	6.2	37.1	0.0	1.1	66.9	15.7	10.4	2.9	1.3	3.2	6.7	12.6	1671
	Test	a	a	a	a	a	a	a	a	a	b	b	a	a	ac		ab	b	b	a	a	a	a	a	a	
Unburnt	**Mean (*C*)**			0				0			0.34			0.51	0.04			0		0.12				0	0	
	St Dev										0.33									0.17					0.0	
	Load (*S*)	0	0	0	0	0	0	0	0	0	1.1	0	0	0.2	0	0	0	0	0	0.1	0	0	0	0	0	1
	Test										c															
1 m buffer	**Mean (*C*)**	0		0				0.27		0.81	3.22		0.76	0.14	0.11		0.15	0.26	0.45	0.22		0.46	0.28	0.27	0.21	
	St Dev							0.48		0.98	1.64		0.96	0.29	0.12			0.28	0.69	0.20		0.71	0.24	0.09	0.12	
	Load (*S*)	0	0	0	0	0	0	2.2	0	6.0	1614	0	4.2	0.3	3.1	0.0	0.1	4.9	3.1	3.8	0	0.6	0.9	0.5	2.4	1646
	Test							a			b		ab	ab	bc			c	bc	a		ab	a	a	a	
5 m buffer	**Mean (*C*)**										0.40		0.30	0	0.05		0.02	0.42	0.08	0.34		0.17	0.09		0.03	
	St Dev										0.37		0.41	0	0.07		0.03	0.68	0.08	0.63		0.09				
	Load (*S*)	0	0	0	0	0	0	0	0	0	45.9	0	1.4	0	0	0	0	5.8	0	2.7	0	0	0	0	0	57
	Test										c		b	b	b		b	bc	c	a		b				
10 m buffer	**Mean (*C*)**	0.20		0				0		0	0.18		0.12	0.08	0.09		0.06	0.13	0.05	0.08	0.06	0	0	0	0	
	St Dev							0			0.31		0.12	0.11	0.15			0.12	0.05	0.11			0			
	Load (*S*)	0.15	0	0	0	0	0	0	0	0	1.57	0	0.28	0.66	0.38	0	0.05	0.8	0.05	0.2	0	0	0	0	0	4
	Test										c															

Appendix 17: Summary statistics for runoff: runoff volume per metre width of hillslope (V) ($L\ m^{-1}$), median runoff volume per sampler (median v) (L), minimum and maximum runoff volumes per sampler (L), and the outcome of Mann Whitney (MW) tests comparing median runoff volumes between treatments for each measurement date (the same letter is applied to treatments with no statistically significant difference, $p > 0.05$). Highlighted cells denote where one or more sampler overflowed and hence the total volume is unknown.

		28-Aug-09	02-Sep-09	07-Sep-09	10-Sep-09	16-Sep-09	18-Sep-09	22-Sep-09	25-Sep-09	30-Sep-09	13-Oct-09	20-Oct-09	27-Nov-09	01-Dec-09	12-Dec-09	06-Jan-10	25-Jan-10	10-Feb-10	16-Feb-10	21-Mar-10	09-Apr-10	29-Apr-10	21-Jun-10	12-Jul-10	26-Jul-10	02-Sep-10	07-Sep-10	19-Oct-10	02-Nov-10	10-Dec-10	Cumulative total (*VO*)
High severity	**Total (*V*)**	42	14	0.3	44	5	8	11	3	141	9	37	196	5	60	18	44	1	7	131	53	55	75	22	2	79	31	28	35	142	1300
	Median v	3	0.9	0	2	0	0.3	0.7	0.1	10	0.5	3	14	0.2	4	1	3	0	0.2	7	2	2	3	0.7	0.2	4	0.8	0.9	2	7	
	Min	0.5	0	0	0	0	0	0	0	0.5	0	0.1	0.7	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Max	>17	7	0.2	>17	5	5	6	2	>17	4	12	>17	2	>17	>17	>17	1	4	>17	>17	65	>17	8	0.5	77	15	>17	>17	64	
	MW-Test	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	ab	a	a	a	a	a	a	a	a	a	a	a	a	a	
Low severity	**Total (*V*)**	58	10	0	27	3	7	11	2	135	7	26	312	2	80	23	99	0	2	121	31	65	84	10	2	39	15	27	36	75	1307
	Median v	4	0.4	0	2	0	0.5	0.7	0.1	7	0.3	1	27	0.0	5	1	5	0	0	5	2	4	4	0.2	0.1	2	0.5	0.5	1	3	
	Min	0	0	0	0	0	0	0	0	0.1	0	0	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Max	>17	8	0	17	4	4	11	2	>17	7	16	>17	1	>17	>17	>17	0.1	1	77	17	59	65	11	0.5	29	22	39	47	83	
	MW-Test	a	a	b	a	a	a	a	a	a	a	b	a	b	a	a	a	b	ac	a	a	a	a	a	a	a	a	a	ab	a	
Unburnt	**Total (*V*)**	0.2	0	0	0.3	0	0.1	0.1	0	1.0	0	0.1	3	0	0.4	0.4	0.6	0	0.1	1.2	0.2	0.8	0.9	0.1	0	1.3	0.4	0.4	0.6	2.3	15
	Median v	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	
	Min	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Max	0.2	0	0	0.3	0	0.1	0	0	1	0	0.1	1	0	0.3	0.5	0.7	0	0.2	1	0.2	0.7	0.6	0.1	0	0.8	0.2	0.3	0.3	1	
	MW-Test	bd	b	b	b	a	b	b	b	b	b	c	c	c	b	b	d	b	c	c	c	c	c	b	c	b	c	b	cd	d	
1 m buffer	**Total (*V*)**	0.4	0	0	0.4	0.1	0.1	0	0	8	0.1	7	502	0.1	6	2	28	0	0.4	19	7	17	15	0.4	1	4	3	2	12		635
	Median v	0	0	0	0	0	0	0	0	0.1	0	0	15.1	0	0.2	0	0.7	0	0	0.7	0.2	0.4	0.6	0	0	0.1	0.1	0.1	0.2	X	
	Min	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	
	Max	0.4	0.1	0	0.4	0.1	0.1	0.1	0.1	>17	0.1	9	>17	0.1	3	0.8	15	0	0.3	13	5	12	8	0.2	0.5	2	>17	0.8	>17	X	
	MW-Test	bc	b	b	b	a	b	b	b	a	b	c	a	c	b	b	bc	b	c	b	b	b	b	b	ab	b	b	b	b	X	
5 m buffer	**Total (*V*)**	0.1	0	0	0.1	0	0	0.1	0	0.4	0	0.1	115	0.1	5	1	10	0	1	14	5	8	5	2	0.5	1	0.5	0.3	0.7	5	175
	Median v	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0	0	0	
	Min	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Max	0.2	0	0	0.1	0	0	0.1	0	0.1	0	0.1	>17	0.2	5	1	8	0	1	11	5	8	2	3	0.5	2	0.4	0.2	1	6	
	MW-Test	b	b	b	b	a	b	b	b	b	b	c	b	c	b	b	cd	b	bc	bc	bc	bc	bc	b	bc	b	c	b	c	d	
10 m buffer	**Total (*V*)**	0.8	0.1	0	0.6	0.1	0.1	0.2	0	1	0	0.4	9	0.1	2	9	5	0	0.9	6	1	2	8	0.4	0.2	5	0.6	0.7	1	6	61
	Median v	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0.1	0.1	0	0	0	0	0	0	0	
	Min	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Max	0.8	0.1	0	0.9	0.1	0.1	0.1	0	1.1	0	0.3	>17	0.1	2	10	7	0	1	7	0.6	1	7	0.5	0.5	7	0.5	0.9	2	3	
	MW-Test	cd	b	b	b	a	b	b	b	b	b	c	c	c	b	b	d	b	bc	bc	bc	b	bc	b	bc	b	c	b	d	e	