MANAGING POST-FIRE SOIL EROSION IN THE SOUTHERN MOUNT LOFTY RANGES

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Abstract

Post-fire soil erosion is a great concern to land managers due to the potential adverse effects on water quality, the alteration to soil profiles and the detrimental impacts on human communities. To reduce the potential adverse effects of post-fire erosion mitigation actions have been instigated following severe wildfires. Various programs of prescribed burning have been initiated to reduce the risk of wildfires. In order to predict and manage post-fire erosion a clear understanding is needed of the influential environmental variables, associated processes and whether mitigation actions will be effective. In the Southern Mount Lofty Ranges there is a paucity of post-fire erosion data from which to generate evidence-based predictive models and management recommendations.

This thesis has the overarching goal of developing evidence-based options for managing post-fire sediment movement in the Southern Mount Lofty Ranges. Evidence-based management of sediment movement from both prescribed fire and wildfire can reduce potential erosion and hence protect regional natural services such as soil profile formation, soil mineral health, the regulation of water quality and maintenance of local landscape character. A case study of the Southern Mount Lofty Ranges is used to produce evidence-based options for managing post-fire erosion in relation to a wildfire at Mount Bold and ten prescribed burns conducted within the Southern Mount Lofty Ranges. Field techniques included visual erosion assessments, erosion pins, terrestrial laser scanning, digital close range photogrammetry and sediment traps. Experiments were designed to incorporate the spatial differences within the topography. Regression modelling was used to analyse environmental variables that influence post-fire sediment movement.

Erosion assessments indicated that after prescribed burning sediment movement occurred in 52% of the burnt areas compared to only 4% in the unburnt areas, however magnitude of movement was only minor. Fire severity was the most influential variable in generating sediment movement after prescribed burning. In contrast slope steepness was the most influential environmental variable in relation to the magnitude of erosion after the 2007 wildfire at Mount Bold. After a 1 in 5 year rainfall event hay-bale sediment barriers will reduce but not prevent post-fire charcoal-rich sediment and debris reaching water reservoirs.

Managing soil erosion in the post-fire landscape requires an appreciation of the influencing environmental variables and the available mitigation options. This thesis highlights the importance of recognising the spatial variability of the topography when managing post-fire erosion. A suite of environmental variables including fire severity, rainfall, aspect, bioturbation, slope length, slope angle and cross-slope curvature need consideration when predicting the occurrence of sediment movement following prescribed fire. Mitigation actions to minimise the adverse effects of post-fire erosion need to take account of rainfall intensity, fire severity and topographical influences. Management of post-fire soil erosion in the Southern Mount Lofty Ranges also needs a recognition of the potential influence on regional natural services including soil profile formation, regulating water quality and maintaining local landscape character.

Contents

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Refereed conference papers

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Conference posters

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Fire note and case study

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Chapter 1: Introduction

Hay bales along the banks of the Onkaparinga River in the Mount Bold reservoir reserve

1.1 Purpose for the research

1.1.1 Erosion and natural services

Soil erosion in the natural landscape is the process of removing and transporting sediment. Accelerated soil erosion is a concern in many parts of Australia (Bui *et al.* 2011; Hatton *et al.* 2011) with the added dimension of soil being considered a non-renewable resource due to its slow rate of formation (Hatton *et al.* 2011). Erosion is a natural process that can be easily accelerated or occasionally decelerated with anthropogenic intervention such as agriculture (Lal 2009; Montgomery 2007), forestry (Croke and Hairsine 2006; Kort *et al.* 1998), mining (Fox 2009; Loch 2000) and urbanisation (Erskine *et al.* 2003; Trimble 1997). Anthropogenic activities associated with soil loss are also associated with the increased likelihood of wildfires (Bajocco *et al.* 2011; Bowman *et al.* 2011; Pyne 1994) and the perceived need to apply prescribed fire as a management option (Adams and Attiwill 2011; Fernandes and Botelho 2003). As natural landscapes continue to be altered by anthropogenic activities the potential for further erosion and subsequent soil loss continues to grow.

Soil is a critical resource for effective natural resource management. Recent debate by Gray (2011) identified the importance of including both biotic ecosystem services and abiotic geosystem services into natural resource management. This thesis considers soil profile formation (Certini 2005; Chafer 2008), soil mineral health (Grady and Hart 2006), regulating water quality (Smith *et al.* 2011) and maintaining local landscape character (Bowman and Boggs 2006) to all be components of geosystem services that are influenced by post-fire soil erosion. Costanza *et al.* (1997) identified numerous ecosystem services and functions that contribute to the world's biotic ecosystems including erosion control, sediment retention, soil formation, nutrient recycling, water supply and cultural opportunities. Rather than debate the relevance of one term over the other in this thesis the term "natural services" is used to incorporate both the abiotic and biotic components of the natural system. Natural services are thus defined as the goods and functional attributes of nature and include both the abiotic and biotic components.

1.1.2 Erosion from wildfires

Fire is a natural process that has played a substantial role in shaping the topography of the earth's surface (Buckman *et al.* 2009; Moody and Martin 2009; Mooney *et al.* 2011; Shakesby and Doerr 2006; Wilkinson and Humphreys 2006). Wildfires alter the attributes of the earth's surface by removing protective vegetation (Gimeno-Garcia *et al.* 2007) and altering soil characteristics (Bento-Gonçalves *et al.* 2012; Certini 2005), resulting in the exposure of the soil surface to rainfall, weathering and erosion (Shakesby 2010; Shakesby *et al.* 2007).

Erosion from wildfires is influenced by many factors including fire severity (Chafer 2008; Dragovich and Morris 2002a, Godson and Stednick 2010; Prosser and Williams 1998; Shakesby 2010), vegetation cover (Benavides-Solorio and MacDonald 2005; Cerda and Doerr 2005; Gimeno-Garcia *et al.* 2007; Johansen *et al.* 2001; Lamb *et al.* 2011; Zierholz *et al.* 1995), soil properties (Certini 2005), terrain features (Marques and Mora 1992; Wilkinson and Humphreys 2006), hydrological properties (Gonzalez-Pelayo *et al.* 2010; Lane *et al.* 2004a, Lane 2006; Moody *et al.* 2008; Shakesby and Doerr 2006), bioturbation (Cerda and Doerr 2009; Dragovich and Morris 2002b; Richards *et al.* 2011; Shakesby *et al.* 2006) and management actions (Cerda and Robichaud 2009). The complex interrelated factors that influence post-fire erosion are often unique to the particular area (Shakesby 2010; Shakesby *et al.* 2007), highlighting the importance for continued field-based studies in different regional settings that can contribute to the broader international assessments.

Scientific interest in the effect of wildfires on soils has increased substantially (Tavsanoglu and Ubeda 2011) due to changing fire regimes (Bowman *et al.* 2011; Bradstock 2010) and the need to sustain the natural services that regulate and maintain environmental health (Costanza *et al.* 1997; Lindenmayer 2003; Loomis *et al.* 2003). There is concern over global climate change (Bowman and Boggs 2006; Pierce *et al.* 2004) and its potential impact on post-fire soil erosion (Nyman *et al.* 2011). Management solutions are needed to minimise detrimental environmental impacts on water reservoir quality (Moody and Martin 2004; Smith *et al.* 2011), soil mineral health and local landscape character. Numerous authors have identified the need to monitor the effects of fire on soil erosion and water catchment conditions (e.g. Bowman and Boggs 2006; Humphreys 1981; Lane *et al.* 2004b; Lindenmayer 2003).

1.1.3 Erosion from prescribed fires

Prescribed fire is similar to wildfire in that it reduces the vegetation cover and alters soil properties. However, the overall fire severity is generally less than a wildfire (Certini 2005) and specific management objectives are applied within a predetermined area (Adams and Attiwill 2011). The use of prescribed fire remains a controversial issue (Adams and Attiwill 2011; Bradstock *et al.* 1998; Oliveras and Bell 2008; Penman *et al.* 2011) partially due to the complex interaction of operational, social and ecological factors (Fernandes and Botelho 2003). Recent debate has focused on the importance of fuel loads: for example, Boer *et al.* (2009) concluded that in the eucalypt forests of SW Australia implementation of widespread prescribed burning has changed fuel age composition and pattern across the landscape and has significantly reduced the incidence and extent of large unplanned fires. In contrast Gibbons *et al*. (2012) argued on the basis of the 2009 Victorian fires that a shift in emphasis away from broad-scale fuel-reduction to intensive fuel treatments close to property would be more effective in mitigating impacts in peri-urban communities. Even the definition of prescribed burning (Adams and Attiwill 2011) differs with community members, scientists, government agencies and other countries all having their own versions. The Australian Fire Authority Council (2012, p. 22) bushfire glossary definition of prescribed burning (see below) is used for this thesis.

"The controlled application of fire under specified environmental conditions to a predetermined area and at the time, intensity, and rate of spread required to attain planned resource management objectives."

Following extreme wildfires, public debate often increases for a change in prescribed burning practices (Carey *et al.* 2003; Jacobson *et al.* 2001; Kanowski *et al.* 2005). The 2009 Victorian Bushfire Royal Commission (Teague *et al*. 2010) recommended that the state implement a long-term prescribed burning program based on an annual rolling target of 5 per cent minimum of public land. In New South Wales (NSW) the NSW 2021 plan released by the Department of Premier and Cabinet (2011) targets a 45% increase by 2016 in the annual average area treated for hazard reduction. Public debate over prescribed burning extends beyond Australia with countries like the United States having groups both recommending and questioning the need to increase prescribed burning (Dombeck *et al.*

2004; Jacobson *et al.* 2001; Wuerthner 2006). Given the post-fire political pressure to increase prescribed burning, it is essential that the impacts on natural services such as soil health and soil erosion are understood and monitored.

Previous research into soil erosion following prescribed burning has reported both high and low magnitude events with various levels of impacts (Cawson *et al.* 2012). Moffet *et al.* (2007) found that soil erosion increased 100 times following the prescribed fire. In the first year post-fire Gimeno-Garcia *et al.* (2007) recorded sediment yields of 561 g m^{-2} from a high intensity fire, versus 326 g m^{-2} following a moderate intensity fire. High magnitude sediment transfer events are possible after prescribed burning as evidenced by the debris flow case study in Victoria described by Cawson *et al.* (2012). Coelho *et al* (2004) found that low intensity fires produced lower sediment yields than wildfires, due to the soil surface being less disturbed and the influence of hydrophilic soil patches. Furthermore, Pierson *et al.* (2009) suggested that the main influencing factors on runoff and sediment yield differed in that soil-water repellency exerts the most influence on runoff, whereas canopy and ground cover have a greater influence on sediment yield. On planar slopes in Victoria Cawson *et al.* (2011) reported that there was minimal difference between high and low severity prescribed fires and suggested that burn patchiness played an important role in reducing sediment movement. Gimeno-Garcia *et al.* (2007) found that rainfall intensity and vegetation cover played an important post-fire role in Mediterranean shrublands.

Varying hydrological conditions can lead to significant differences in suspended sediment and nutrient exports within the first 12–18 months after prescribed fires (Smith *et al.* 2010). Wohlgemuth *et al.* (1999) reported that a wildfire generated ten times as much sediment as a prescribed burn in the first post-fire winter. Given the unanimous conclusion that prescribed fire is likely to increase sediment movement, there is clearly a need for studies into management of erosion from prescribed burning. Better understanding is needed of the possible benefits of prescribed burning for reducing potential erosion from more severe wildfires.

Within Australia each State has its own system for assessment of erosion potential but these vary widely. For example in New South Wales a code has been developed to streamline environmental approval for hazard reduction works (Brompton *et al.* 2006). In NSW, if a soil erosion risk map does not exist, moderate or higher fire intensities are not to be used on slopes steeper than 18 degrees. In South Australia managers use conceptual models in relation to predicting potential erosion and are currently in the process of developing various new written guidelines. Worldwide, such differences are also apparent among countries as evident in differing legislation and assessment protocols. For example the USA on federal land applies the Healthy Forest Restoration Act of 2003 (O'Laughlin 2005) while England applies regulations 2007 that restrict certain areas of burning to 10 ha in order to protect the soil and water courses (Bruce *et al.* 2010). Given the emerging information about soil erosion following prescribed burning there is a need to determine if existing erosion prediction methods are adequate and whether appropriate monitoring is undertaken to confirm the adequacy of erosion predictions.

1.1.4 Managing post-fire erosion

Managing post-fire erosion requires an understanding of the potential risks and the possible mitigation strategies that can be employed (Benavides-Solorio and MacDonald 2005; Robichaud and Ashmun 2012). Adverse consequences of post-fire erosion have included loss of life (Cannon and DeGraff 2009), destruction of human infrastructure (Nyman *et al.* 2011) and detrimental impacts to water supply catchments (Smith *et al.* 2011; White *et al.* 2006). Research by Gunn (2011) on rock art and rock shelters did not find any immediate deleterious impacts, however the author highlighted that when the impact is adverse it can be dramatic and catastrophic.

Natural resource managers have expressed concern over the post-burn spread of *Phytophthora* via water and fire-fighting equipment (DEH 2006). It has been suggested that prescribed fire may assist in managing *Phytophthora* in forest ecosystems (Dawson *et al.* 1985; Moritz and Odion 2005), but Meadows *et al*. (2011) found no direct effect of fuel reduction treatments on the incidence of *Phytophthora* in soil. Given that *Phytophthora* is spread through spores within the soil (Goodwin 1997), further research is required about its spread by post-fire soil erosion, especially under differing fire severities and frequencies. Understanding the processes and quantity of soil erosion post-fire is essential to managing potential adverse consequences.

Aborigines, foresters and farmers have historically used fire for land cleansing and clearing (Pyne 1994, 2006). Academic debate has been generated over whether Aboriginal landscape burning triggered geomorphological instability, but there is no clear sedimentary evidence to support any definitive conclusions (Bowman 1998).

Numerous authors have reported that there is a loss of soil nutrients after fire (Smith *et al.* 2010; Wright *et al.* 1976). McIntosh (2005) argued that the increased availability of nutrients at the soil surface after fires leads to decreased total nutrients and decreased nutrient availability in the long term. This theory is difficult to prove due to the complex nature of erosion (Stroosnijder 2005) and the substantial redistribution of sediment that occurs post-fire (Martin *et al.* 2008; Shakesby *et al.* 2006).

Although prescribed fire poses many risks it has also proven to be advantageous. Loomis *et al*. (2003) and Wohlgemuth *et al*. (1999) argued that prescribed fire may actually reduce the loss of nutrients by minimising the amount of erosion compared to wildfire. Wohlegemuth *et al*. (1999) suggested that prescribed fire can be an effective and economically viable sediment management tool. Loomis *et al.* (2003) considered the economic costs of five-year fire intervals on catchment sediment yield. They argued that a direct cost savings of $24 million was possible by reducing the fire interval from the current average 22 years to a prescribed fire interval of five years resulting in a sediment yield reduction of 2 million m^3 in a 86 km^2 watershed in southern California. Land managers are faced with the compromise between prescribed burning to reduce fuel loads and maintaining adequate cover of ground litter to mitigate against potential soil erosion (Gill *et al.* 2008; Good 1994). There is a clear need to improve our understanding of the management of potential soil erosion post-prescribed fire.

Management of post-fire erosion can be divided into three approaches: i) using preventative measures to eliminate the problem before it occurs, ii) using mitigation strategies after the fire event to reduce the potential impacts, or iii) no action. These differing approaches are now discussed.

Preventative measures to eliminate the risk of post-fire erosion to date have received minimal academic interest. Loomis *et al*. (2003) and Wohlgemuth *et al*. (1999) suggested the use of prescribed burning to minimise the potential amount of erosion that follows a major wildfire. Many water authorities have used the preventative approach of extinguishing any wildfire before it reaches the water catchment. Management teams such as the Victorian Bushfire RRATs (bushfire rapid risk assessment teams), NSW/ACT BAAT (burnt area assessment team) (PCL and NPWS 2010), or United States Department of Agriculture Forest Service BAER (burned area emergency rehabilitation) (Robichaud *et al.* 2000) have been established and trained to be deployed should a substantial wildfire occur. Although these teams are initially a preventative treatment they still rely on applying mitigation strategies to reduce potential soil erosion.

The use of mitigation strategies generally occur after major wildfires (Cerda and Robichaud 2009). Robichaud and Ashmun (2012) described numerous 'tools' that have been developed in the US to assist land managers with post-wildfire assessment and treatment decisions. Examples of the US 'tools' include prediction models, research syntheses, methods for field measurements, databases of past-practice, and spreadsheets for calculating cost-benefit analysis. In Australia these 'tools' were trialled following the 2009 Victorian fires (Robichaud and Ashmun 2012) however they are yet to be implemented in other areas.

Active mitigation of post-fire erosion often involves the use of sediment barriers (deWolfe *et al.* 2008; Hobson *et al.* 2004; Robichaud 2005). Robichauld (2005) found that post-fire rehabilitation techniques (including broadcast seeding, mulching and installed sediment barriers) cannot prevent erosion; however the active measures can reduce overland flow, site soil loss and sedimentation for some rainfall events. Fox (2011) reported that where pine trees were available, log debris dams were relatively efficient and cost effective for trapping sand-sized sediments; however he also recommended using log erosion barriers, as they maintained soil on hillslopes. He noted that although sedimentation basins were more expensive they were a more effective method for trapping sediments.

Post-fire erosion mitigation tends to be used infrequently except in the western US (Robichaud and Cerda 2009). Due to the unique post-fire characteristics of south-east Australia as identified by Shakesby *et al.* (2007) it is questionable whether post-fire mitigation strategies in Australia are essential. The 'no action' approach to manage erosion after prescribed burning is a common but rarely documented decision. After the 1994 fires in Sydney Royal National Park, Hairsine (1997) supported the 'no action' approach except for areas where flow needed to be slowed and dispersed near tracks and trails. Many of the plant species in sclerophyll vegetation in southern Australia do not experience catastrophic mortality in large fires due to their ability to resprout (Bradstock 2008). Although southern Australia has unique post-fire characteristics there is a clear need to understand soil erosion post-fire especially in light of the erosion following the Victorian 2003 and 2009 fires (Smith *et al.* 2011) and the water quality issues following the Canberra 2003 fires (White *et al.* 2006). Implementation of future post-fire mitigation strategies requires an understanding of both the erosion processes and the potential benefit of differing mitigation strategies.

1.1.5 Southern Mount Lofty Ranges case study

The Southern Mount Lofty Ranges are located in South Australia (Figure 1), in a temperate, Mediterranean-type climate zone where wildfires occur due to warm to hot, dry summers. The following winter months bring mild to cool, wet weather. The long-term official Bureau of Meteorology weather station is located at Mount Barker (station ID 023733; 35.06° S 138.85° E; elevation 363 m). Mean annual rainfall at Mount Barker from 1986 to 2011 was 765 mm, with the highest rainfall occurring during the winter months. Total annual rainfall at Mount Barker in 2008 was 584 mm and in 2009 was 814 mm. As elevation increases, annual rainfall increases, as is evident at Piccadilly in the Mount Lofty Botanic Gardens, where the total annual rainfall in 2008 was 1016 mm and in 2009 was 1280 mm (Australian Bureau of Meteorology Piccadilly weather station ID 023788; 34.98 °S 138.72 °E; elevation 510 m).

The study area is composed of deformed Proterozoic and Cambrian sedimentary rocks of the Adelaide Fold Belt, which include quartzite, shale, dolomite, sandstone and conglomerate lithologies (Daily *et al.* 1976; GSAA 1962). The geomorphological evolution of the Southern Mount Lofty Ranges is the result of faulting, weathering, erosion and deposition over a vast period of geological time dating back to the late Palaeozoic age (Twidale 1976). Soils are predominantly shallow to moderately deep acidic soils on rock (Soil and Land Program 2007). The topography is dissected by small tributaries that feed into the Gawler, Torrens and Onkaparinga Rivers. Over ten percent of the study area has slope angles greater than 18 degrees (Figure 1). The Mount Lofty Ranges are susceptible to erosion with a total of approximately 40% of the area estimated to have erosion rates of above 1 t/ha/y (Wilkinson *et al.* 2005). Native vegetation predominantly consists of dry *Eucalypt* forests and woodlands, with either grassy or shrubby understories (Armstrong *et al.* 2003).

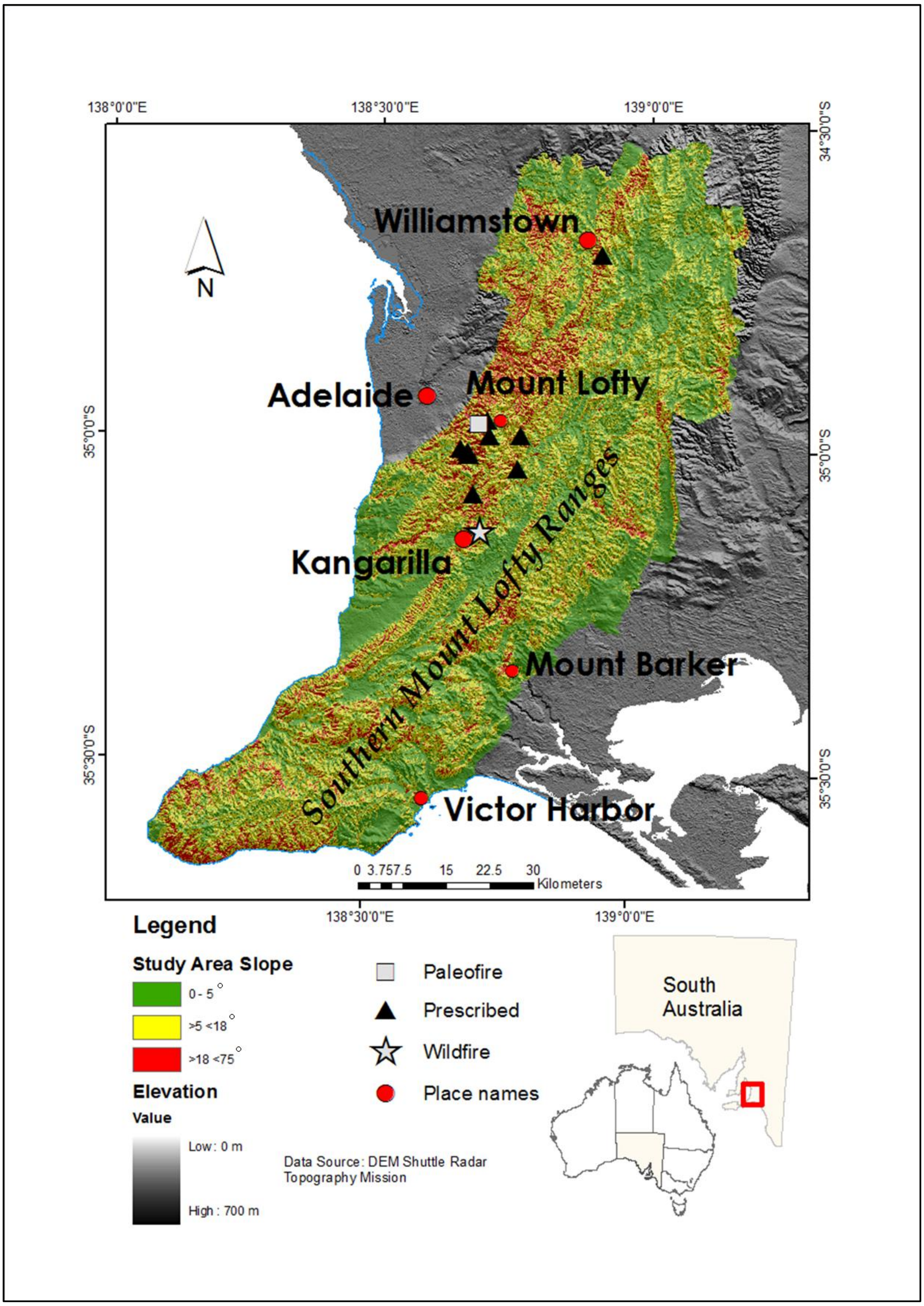

Figure 1: Location map of the Southern Mount Lofty Ranges showing the fires researched as part of this thesis and the slope steepness within the study area.

Wildfires

The Southern Mount Lofty Ranges have experienced many wildfires both in the past and recent geological times. Knowledge of wildfire history is essential to appreciate the response and resilience of the natural services to post-fire change. Existing palaeofire evidence (Bickford and Gell 2005; Buckman *et al.* 2009) in the study area includes the Boat Harbour peat swamp in the Fleurieu Peninsula and Wilson Bog near Mount Lofty. At the Boat Harbour swamp, dating of charcoal from soil cores indicated the presence of fire for the past 8000 years before present (BP) (Bickford and Gell 2005). Analysis of charcoal in sediments at Wilson Bog recorded at least fifteen separate fire events that caused post-fire deposition during the period from 6000yr BP (Buckman *et al.* 2009 see Appendix A). Both of these dates indicate the presence of fire prior to European settlement.

Since European settlement began in the Mount Lofty Ranges the most well-known fire, 'Ash Wednesday' occurred in 1983, resulting in the loss of 28 South Australian lives, injuries to 2143 people, destruction of 207 homes and over 200 000 ha burnt (Healey *et al.* 1985). Since Ash Wednesday the largest fires have been the Black Hill fire in 1985 (1617 ha), Mount Torrens fire in 1996 (3154 ha) and then the Mount Bold wildfire in 2007 (1550 ha) (DEWNR Fire History database). In total 186 wildfires burning 10 500 ha have been recorded between July 2001 and June 2010 (DEWNR fire database). Many of the wildfires are attributed to anthropogenic ignitions, including campfires, car fires, suspected arson, burn-offs on adjacent land and sparks from machinery use (DEH 2009). The most frequent cause of ignition is suspected arson (DEH 2009).

In South Australia the mission of the Country Fire Service (CFS) is "to protect life, property and the environment from fire and other emergencies whilst protecting and supporting their personnel and continuously improving" (CFS 2010, p. 6). Department of Environment, Water and Natural Resources (DEWNR- formerly known as DEH or DENR) has a similar approach with their first objective being "to provide for the protection of human life and property" (DEH 2009, p. 2). To achieve these outcomes a variety of fire-planning and operational approaches are taken. In relation to wildfires, the main response is containment and suppression. Fire management in South Australia is a collaborative effort involving mainly the CFS, DEWNR, South Australia Water Cooperation (SA Water) and Forestry SA.

Prescribed fires

Local fire authorities currently use prescribed burning to reduce fuel loads in order to minimise the intensity and risk of wildfires. The re-emerged use of prescribed burning in the Mount Lofty Ranges can be partially attributed to the Bushfire Summit held in 2003 (Richards 2006). Policy changes within organisations such as the SA Water have moved from a ‘no burn’ approach prior to 2008 to implementing prescribed fire within water reserves (SA Water 2008 prescribed burning policy CP 064 V2.0 AM). Prior to 2009, most of the recorded prescribed burns were conducted in DEWNR-managed lands. Since 2006, fire authorities have increased the amount of prescribed burning conducted in the study area. When the Mount Lofty Ranges Fire Cooperative commenced in 2009 DEWNR, SA Country Fire Service, SA Water and Forestry SA began to work in partnership to reduce fire risk and to protect public and private lands from wildfire.

Prior to burning in South Australia an environmental assessment is required under the Native Vegetation Act that includes the requirement for erosion issues to be addressed. Previous environmental reviews (Table 1) have frequently focused on slope steepness in relation to erosion concerns after prescribed burning. Considering the extensive research (Bento-Gonçalves *et al.* 2012; Shakesby and Doerr 2006; Shakesby *et al.* 2007) into the many variables that influence post-fire erosion it is questionable whether the threshold of an 18-degree slope is actually the major environmental variable that needs consideration in environmental assessments. In NSW a code has been developed to streamline environmental approval for hazard reduction works (Brompton *et al.* 2006) that includes using the soil erosion models based on the Revised Universal Soil Loss Equation (RUSLE) developed by Yang and Chapman (2006). The Disturbed Water Erosion Prediction Project (WEPP) and the GeoWEPP models have been applied to assess potential erosion from prescribed burning in the western US (Miller *et al.* 2011). In order for land managers to successfully assess potential erosion in South Australia there is a need for a probability model that encompasses the main variables influencing post-fire erosion.

Table 1. Excerpts in relation to erosion from the unpublished Part A environmental assessment tables completed to meet provisions under the South Australian *Native Vegetation Act 1991*.

Burn Name Reserve	Land Manager	Consideration	Potential impacts
Belair S09	DEH	Potential to alter erosion potential, particularly in areas with steep slopes (>18 degrees)	Slopes typically less than 18 degrees. No impact predicted.
Berri Werri	DEH	Potential to alter erosion potential, particularly in areas with steep slopes (>18 degrees)	While slopes within the burn site are between 20 - 30 degrees, erosion is likely to be minimal due to the mosaic and small size of the burn
Cleland S09b	DEH	Potential to alter erosion potential, particularly in areas with steep slopes (>18 degrees)	The burn site consists of moderate slopes. There is the potential for erosion, particularly in drainage lines. A low intensity burn allows much of the flora, particularly the resprouters, to re-establish cover rapidly after burning which will help mitigate erosion.
Gate 17	DEH	Potential to alter erosion potential, particularly in areas with steep slopes (>18 degrees)	Slopes typically less than 18 degrees. No impact predicted.
Kangaroo Gully	DEH	Potential to alter erosion potential, particularly in areas with steep slopes (>18 degrees)	Slopes on the site are generally less than <18 degrees. Erosion is likely to be minimised due to the mosaic and low intensity prescription of burn.
Mount Lofty S09	Botanic Gardens	Potential to alter erosion potential, particularly in areas with steep slopes (>18 degrees)	There is unlikely to be any erosion on this site due to its gentle slope <20 degrees
Warren	SA Water*	The proposed burn area is on a 5º - 10º slope on acidic gradational sandy loam on rock with high erosion potential.	Depending on the intensity of the burn there may be some erosion in places.
Wildlife	DEH	Potential to alter erosion potential, particularly in areas with steep slopes (>18 degrees)	Site is along a ridge line with lower sections recording slopes of up to 20 degrees. Erosion should be minimised due to the mosaic and low intensity prescription of burn .
Wottons Scrub	DEH	Potential to alter erosion potential, particularly in areas with steep slopes (>18 degrees)	Erosion will be minimized due to the mosaic and low intensity prescription of burn. Large fallen timber, remaining unburnt material and regenerating vegetation will slow runoff and reduce erosion potential of steeper slopes
Mylor S09	DEH	Potential to alter erosion potential, particularly in areas with steep slopes (>18 degrees)	Erosion potential is low due to the gentle slopes at the burn site and the small size of the burn.

*SA Water also addressed additional actions (see below) to minimise erosion in the Part A table for the Warren prescribed burn.

> "undertake the burn on a day with high relative humidity and/or low temperature early in the season (i.e. mid to late September). This should result in a patchy burn leaving organic matter intact and the wet gullies unburnt. This should minimise the likelihood of erosion. In addition, a spring burn is less likely to be followed by heavy rains also reducing the likelihood of erosion"

The Mount Lofty catchment provides 60% (on average) of Adelaide's water supply, which could be affected in the event of sedimentation following fire. To date strategies to reduce erosion and sedimentation within water reservoir reserves have included fire avoidance, sediment trapping (Hobson *et al.* 2004, SA Water 2007a) and a detailed written fire recovery strategy that covers a risk assessment and operational response for each individual reservoir (SAWater 2007b). In the DEWNR there are fire management plans for each reserve and written policy and procedure for post-fire rehabilitation. An assessment by Bardsley (2006) of projected climate change impacts and adaptation options for Natural Resource Management in the Adelaide and Mt Lofty Ranges Region reported that changing climates will alter the productivity of natural systems, and hence the fuel loads, but also the rate and intensity of fires. Bardsley (2006) also reported that prescribed burning opportunities may become less frequent. Further attention is warranted by land managers on considering the importance of optimal spatial location of prescribed burning and suitable fire regimes in order to reduce possible post-fire erosion and sedimentation.

1.1.6 Evidence-based management

A critical mass of research into post-fire erosion has resulted in numerous major reviews being published in international journals. These papers review the influence of fire on hydrology and geomorphology (Bowman and Boggs 2006; Shakesby and Doerr 2006), soil erosion of south-east Australian *Eucalypt* forests in a global context (Shakesby *et al.* 2007), Mediterranean soil erosion (Shakesby 2010), fire effects on water quality in forest catchments (Smith *et al.* 2011) and the management responses of post-fire seeding in western USA (Peppin *et al.* 2010). To date there are numerous case studies (deWolfe *et al.* 2008; Fox 2011; Hobson *et al.* 2004; Robichaud 2005) on the use of erosion barrier traps, however a comprehensive international review is still needed. Often sediment trapping records are difficult to access due to their unpublished status in government departments. To date hillslope stabilisation occurs mostly in western USA (Robichaud and Cerda 2009).

Current environmental management policies and scientific papers often refer to using evidence-based management (Burrows 2008; Productivity Commission 2009) or implementing adaptive management (Bradstock 2008; Chapple *et al.* 2011; Keene and Pullin 2011; Penman *et al.* 2011). These two terms are related because as more evidence becomes available current management practices may need to be adapted to accommodate this new information. In many cases fire managers are making decisions with minimal post-fire erosion evidence, as localised fire regimes may have inter-fire intervals of greater than 10 years (Bradstock 2010) and each major wildfire may or may not be followed by a major rainfall event resulting in substantial erosion (Prosser and Williams 1998; Tomkins *et al.* 2008). There is a paucity of data that records the amounts of erosion occurring in the post-fire environment under natural rainfall or wind conditions.

Applying evidence-based management relies not only on understanding the erosion processes but also on appreciating whether these processes are actually occurring in the area of interest. Often decisions need to be made using the best available information obtained either from theoretical knowledge, modelling or from differing spatial locations to where the fire event occurred. Current advances in modelling (Jones *et al.* 2011) that intersect burnt forest and convective thunderstorms are providing interesting outcomes to aid future management decisions. These models still require field-based observations to validate their outcomes within differing spatial contexts. Miller *et al.* (2011) highlighted that the recent prediction of potential post-fire erosion rates from fuel treatments in the western USA was hampered by the lack of field data for the diverse landscapes.

A recent review by Peppin *et al.* (2010) focused on the quality of evidence using a systematic search protocol described by Pullin and Stewart (2006). After applying the systematic search protocol to post-wildfire seeding treatments in western USA the authors reviewed 19,455 studies within the literature of which 94 were considered relevant in relation to their specified inclusion criteria. On this basis, they concluded that post-wildfire seeding does little to protect soil in the short-term and that long-term studies were still needed. The authors further reported that there is a spatial difference in the success of seeding based on differing rainfall characteristics. The spatial difference in seeding success highlights the importance of conducting soil erosion studies in differing locations such as the Mount Lofty Ranges in South Australia where there has been no previous post-fire soil erosion research to my knowledge.

A systematic evidence review similar to that of Peppin *et al.* (2010) is not possible for the management of post-fire erosion in South Australia, as there is a paucity of published information on which to base the evidence. Oliveras and Bell (2008) reported that of the 576 Australian publications reviewed in relation to prescribed burning between 1960 and 2006, only 5 out of the 576 papers were conducted in South Australia. Of the 576 papers reviewed nation-wide only 330 scientific and technical publications had an ecological focus of which only 17% dealt with soil-related topics and only 4% were concerned with water. There is currently substantial research into the processes of post-fire soil erosion in south-east Australia (Shakesby *et al.* 2007), however there is a paucity of research or monitoring that analyses post-fire erosion in Australia from prescribed burning (Cawson *et al.* 2011). There is also a research gap into the effectiveness of management strategies to remediate post-fire erosion after both prescribed and wildfires. In order to apply evidence-based adaptive management in South Australia it is essential that the evidence-gathering process is increased.

1.1.7 Summary

Post-fire erosion influences natural services by altering water quality (Smith *et al.* 2011), soil profile development (Certini 2005; McIntosh *et al.* 2005) and general landscape characteristics (Shakesby and Doerr 2006). Although there are numerous international reviews (Bento-Gonçalves *et al.* 2012; Bowman and Boggs 2006; Shakesby and Doerr 2006; Shakesby *et al.* 2007) covering post-fire erosion there still exists a research need to develop field-based evidence for the management of post-fire erosion in the Southern Mount Lofty Ranges. The monitoring and measurement of erosion is a complex task (Stroosnijder 2005) which when combined with the uncertainty of fires and subsequent rainfall events (Jones *et al.* 2011) limits the capacity of managers to adequately assess post-fire erosion. In order to empower land managers with the ability to collect evidence in relation to post-fire erosion a simple operational assessment technique needs to be developed.

As prescribed burning continues to be used to manage fuels and to conduct ecological burns, localised evidence is required to determine whether prescribed burning causes erosion in the Southern Mount Lofty Ranges and whether simple models can predict potential erosion. There is a need to determine if sediment barriers will mitigate erosion problems in the study area, especially in relation to water reservoir reserves. Evidence-based research is required to determine the ideal positioning of sediment barriers in relation to post-wildfire erosion. We need to understand the erosion processes and potential management actions that can be taken in the event of fire.

1.2 Aims of the thesis

This thesis has the overarching goal of developing evidence-based options for managing post-fire sediment movement in the Southern Mount Lofty Ranges. Evidence-based management of sediment movement from both prescribed fire and wildfire can reduce potential erosion and hence protect regional natural services such as soil profile formation, soil mineral health, the regulation of water quality and maintenance of local landscape character.

Aim 1: To evaluate various methods of assessing post-fire erosion in the Southern Mount Lofty Ranges.

- Eight methods were trialled and reviewed in the context of simple operational use, associated costs, and application to different timeframes, spatial scales, magnitude and frequency. On the basis of this information a simple method, suitable for use by land managers in assessing and monitoring sediment movement post-prescribed burning, was developed.

Aim 2: To identify what environmental determinants influence sediment movement from prescribed burning in the Southern Mount Lofty Ranges.

- Prescribed burns were assessed to determine if soil erosion increased following fire. Regression modelling was undertaken to determine which variables can predict the probability of sediment movement occurring.

Aim 3: To determine if management intervention could prevent sediment movement post-wildfire.

- The effectiveness of constructed sediment traps to reduce mobilised sediment from reaching the water reservoir was investigated. Basic recommendations to assist managers in locating and designing sediment traps for future wildfire events were developed.

Aim 4: To assess hillslope erosion in relation to post-wildfire sediment trapping at the water reservoir at Mount Bold.

- Hillslope surface change was quantified using erosion pins, terrestrial laser scanning and sediment traps after a 1 in 5 year rainfall event. The influence of slope gradient, slope length, cross-slope curvature, hillslope position and fire severity in relation to surface change was assessed.

1.3 Structure of the thesis

This thesis is structured with six chapters comprising of introduction (Chapter 1), portfolio of papers/manuscript (Chapters 2-5) and concluding discussion (Chapter 6) followed by appendices.

The introduction (Chapter 1) provides a contextual statement which includes a literature review establishing the field of knowledge in relation to managing post-fire erosion. This literature underpins the research problems identified, defining the overarching goal and aims of the thesis. The chapter concludes with an outline of the thesis structure (Chapter 1).

Chapter 2 applies and reviews methods used to monitor post-fire erosion in the Mount Lofty Ranges in the context of simplicity for land management staff and researchers. They are further examined in relation to different timeframes, spatial scales, magnitudes and frequency. A visual assessment framework is described to classify different levels of sediment movement post-fire. This chapter was presented as a refereed conference paper.

Morris R, Buckman S, Connelly P, Dragovich D, Ostendorf B, Bradstock R (2011) The dirt on assessing post-fire erosion in the Mount Lofty Ranges: comparing methods. In Thornton RP (Ed) 2011 'Proceedings of Bushfire CRC and AFAC 2011 Conference Science Day' 1 September 2011, Sydney Australia, 152-169. (Bushfire CRC: Melbourne)

The classification method described in Chapter 2 is applied in Chapter 3 to monitor post-fire erosion after prescribed burning of ten sites located in the Mount Lofty Ranges. The prescribed burns were assessed to determine whether soil erosion occurred following fire. A regression model was developed to determine which variables could be used to predict the probability of sediment movement occurring. South Australian environmental erosion assessments completed for the ten burns were reviewed in light of the evidence-based results. This chapter was submitted as a manuscript to the *International Journal of Wildland Fire* on 19 January 2013.

Morris RH, Bradstock RA, Dragovich D, Henderson MK, Penman TD, Ostendorf B (submitted) Environmental assessment of erosion following prescribed burning in the Mount Lofty Ranges, Australia.

Chapter 4 assesses the management intervention at Mount Bold to prevent sediment accumulation in the water reservoir system after a wildfire in 2007. Basic recommendations are provided to assist land managers in locating and designing traps for future wildfire events. This chapter was presented as a refereed conference paper.

Morris R, Calliss S, Frizenschaf J, Blason M, Dragovich D, Henderson M, Ostendorf B (2008) Controlling sediment movement following bushfire - a case study in managing water quality, Mount Bold, South Australia. In Lambert M, Daniell T, Leonard M (Eds) 'Proceedings, Water Down Under 2008 Conference, incorporating 31st Hydrology and Water Resources Symposium and 4th International Conference on Water Resources and Environment Research' 14-17 April 2008, Adelaide, Australia, 1937-1947. (Engineers Australia: Modbury)

Chapter 5 complements Chapter 4 by assessing how hillslope morphology can influence post-fire surface erosion and subsequently influence post-fire sediment trapping. Slope gradient, slope length, cross-slope curvature, hillslope position and fire severity is measured in relation to surface change and sediment trap success. This chapter was presented as a refereed conference paper.

Morris R, Dragovich D, Ostendorf B (2012) Hillslope erosion and post-fire sediment trapping at Mount Bold, South Australia. In Stone M, Collins A, Martin T (Eds) 'Wildfire and water quality: processes, impacts and challenges' Banff, Canada, 11–14 June 2012. *IAHS Publication* 354, 42-50. (IAHS Publication: Oxfordshire)

Chapter 6 reviews the findings of the research and the overall significance and contribution to knowledge. Problems encountered with the research are discussed and future research directions are suggested. The thesis concludes with management suggestions and a summary of the major research outcomes.

The Appendices include a published journal paper, conference paper, seven conference posters and two information brochures that are all based on research done concomitantly with that for this thesis and which are related to the presented thesis research.

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Chapter 2: Comparison of post-fire soil erosion assessment methods

Terrestrial laser scanner near the Onkaparinga river at Mount Bold reservoir reserve

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2.1 Copyright details

Copyright holder of the work:

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2.2 Statement of contribution

As primary author I was responsible for the conceptualisation of the work by deciding on the project proposal, the methodology and liaising with the relevant land management agencies including DEWNR, SA Water and the Botanic Gardens. I was involved in the realisation by coordinating and completing all differing field components, data analysis and the primary preparation of the manuscript. The role of S Buckman was in relation to the stratigraphic analysis and minor edits of the manuscript. The role of P Connelly was the conceptualisation and realisation of the digital close range photogrammetry and minor edits of the manuscript. The role of D Dragovich, B Ostendorf and R Bradstock was advice on the research conceptualisation and editing of the manuscript. B Ostendorf also assisted in the fieldwork for the laser scanning and digital close range photogrammetry. I presented the paper at the 'Conference Science Day' of the Bushfire CRC and AFAC Conference on 1 September 2011 in Sydney, Australia. Two anonymous reviewers provided comments on the paper.

I hereby certify that the statement of contribution is correct.

R Morris (Candidate) 23/1/13 Date

I hereby certify that the statement of contribution is correct and I give permission for the inclusion of the paper in the thesis.

S Buckman 29/1/13 Date

P Connelly 25/1/13 Date

D Dragovich 31-1-13 Date

B Ostendorf 23-1-13 Date

R Bradstock 1/2/13 Date

The dirt on assessing post-fire erosion in the Mount Lofty Ranges: comparing methods

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Abstract

Land managers are required to assess a range of environmental attributes prior to and after prescribed burning. Current environmental assessments vary depending on the organisation involved and the existing information about localised soil erosion. Auditing successful environmental assessments requires ongoing field monitoring to evaluate whether the magnitude and extent of predicted post-fire impacts are comparable. The impacts of post-fire erosion were assessed by the authors using the techniques of water sampling, sediment traps, erosion pins, laser scanning, photogrammetry and visual field assessment. Each data collecting method varies in its spatial and temporal reach in terms of monitoring landscape changes in a post-fire environment. The methods also vary in cost, time and technical complexity.

This paper uses a case study of the Mount Lofty Ranges, South Australia to apply and assess post-fire erosion field techniques in relation to a wildfire at Mount Bold, a Holocene paleofire located at Cleland and ten prescribed burns conducted within the Mount Lofty Ranges. The techniques are assessed for their merits in the context of simplicity for land management staff to use and associated costs. They are further examined in light of their application to different timeframes, spatial scales, magnitude and frequency. Our investigation leads to the recommendation of a simple framework for quick and relatively easy assessment, which is cost effective and can be carried out by both researchers and land management agencies.

Additional keywords: spatial scale, soil loss, laser scanning, prescribed burning, wildfire, environmental assessment

Introduction

Managing erosion in a fire prone landscape requires an appreciation of the diverse processes that influence the movement of sediment. The accurate prediction of post-fire erosion still remains an unresolved problem (Moody and Martin 2009). Moderate- to high-magnitude erosion events have received considerable attention (Certini 2005; Shakesby 2010; Shakesby and Doerr 2006; Shakesby *et al.* 2007) due to the significant difference between post-fire sediment movement and natural denudation rates (Lane *et al.* 2006; Tomkins *et al.* 2007); and the detrimental impact on water supply catchments (Moody and Martin 2004; Smith *et al.* 2011; White *et al.* 2006) and human infrastructure (Nyman *et al.* 2011). In contrast there is a paucity of research (Cerda and Lasanta 2005; Coelho *et al.* 2004; Moffet *et al.* 2007; Smith *et al.* 2010) into low-magnitude erosion events that typically follow prescribed burning.

Over the past ten years there has been a shift towards increasing prescribed burning in South Australia in part due to the Bushfire Summit held in 2003 (Richards 2006). This trend has continued in Victoria with the 2009 Victorian Bushfire Royal Commission (Teague *et al.* 2010) recommending that the state implement a long-term prescribed burning program based on an annual rolling target of 5 per cent minimum of public land. This shift towards increased prescribed burning increases the importance of monitoring in post-fire landscapes. Managers require evidence-based management strategies that address landscape characteristics of the burnt site, the timing of the burn in relation to known rainfall patterns and what ignition patterns are used to modify the fire severity. In South Australia, consideration of potential soil erosion is a legislative requirement (Department for Environment and Heritage 2009) prior to approval of prescribed burning, and an affordable simple technique is needed for land managers to audit this process post-fire.

Considerable technological developments have occurred since Loughran (1989) reviewed the measurement of soil erosion. New technologies such as digital close-range photogrammetry (Heng *et al.* 2010) and laser scanning (Heritage and Hetherington 2007) have enhanced our ability to measure erosion. However, these technologies currently require specialised technical skills to undertake the surveys and process the data so they currently have limited practical application to post-fire landscapes, particularly in remote areas. There is a need to review, assess and compare a variety of post-fire erosion field techniques for both research and land management purposes.

This paper discusses the merits of applying and assessing various post-fire erosion field techniques used in the Mount Lofty Ranges in the context of simple operational use, associated costs, application to different timeframes, spatial scales, magnitude and frequency of erosion events. The comparison includes a simple rapid visual post-fire erosion assessment framework, developed for auditing the accuracy of prescribed fire environmental assessments of post-fire erosion.

Study site

Field-based assessment of post-fire erosion was conducted in the Mount Lofty Ranges (Fig. 1) and focuses on an area to the east of Adelaide where the elevation reaches 727 m at Mount Lofty (34º58'36"S, 138º42' 35"E). The slope is often greater than 18 degrees and is dissected by small tributaries that feed into the Gawler, Torrens and Onkaparinga Rivers.

Precambrian and Cambrian basement rocks are mantled by shallow to moderately deep acidic soils with high erosion potential (Soil and Land Program 2007). The area lies in a temperate climate zone with warm, dry summers and cool, wet winters. Mean annual rainfall at Mount Barker is 764 mm (Bureau of Meteorology 2010). Native vegetation predominantly consists of dry eucalypt forests and woodlands with either grassy or shrubby understoreys.

The study area has not experienced a major wildfire since Ash Wednesday in 1983 (Department of Environment and Natural Resources GIS fire history). Every year numerous fires are ignited but they rarely reach a sufficient size, such as 1000 ha, to result in major erosion events. In 2007 substantial sediment movement was recorded after a wildfire that burnt 1700 ha at Mount Bold (Morris *et al.* 2008a). The Mount Bold wildfire, ten prescribed burns and paleofire records from Wilson Bog in Cleland are used as case studies for this paper (Fig.1). All sites are located east of Adelaide in the Mount Lofty Ranges. The prescribed burns were conducted between 2007 and 2009 with an average area of 14 ha.

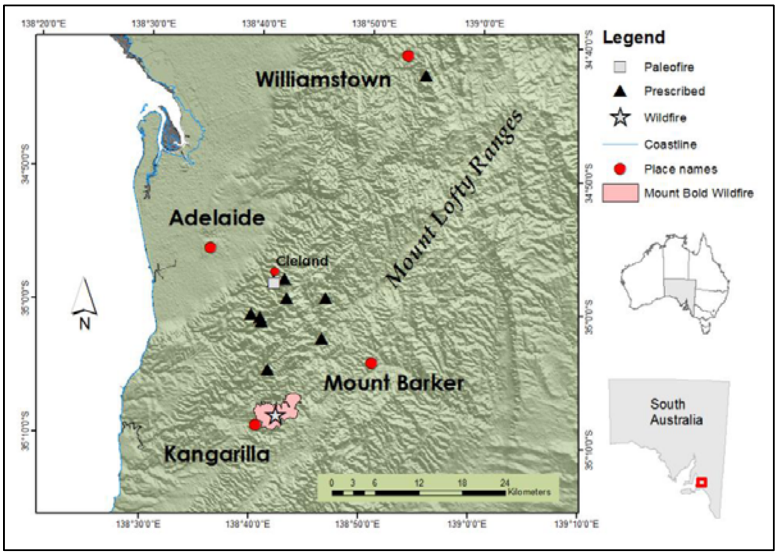

Fig. 1. Location map of the paleofire, wildfire and prescribed fires assessed in the Mount Lofty Ranges, South Australia. (DEM sourced from Shuttle Radar Topography Mission data)

Post-fire erosion assessment in the Mount Lofty Ranges

Selection of the most appropriate method to assess post-fire erosion depends on the temporal scale at which the threat is assessed, the spatial scale of operations, the likely event magnitude and the land management priorities. In the Mount Lofty Ranges various methods were applied by the authors in the post-fire landscape, including water sampling, sediment traps, stratigraphic analysis, erosion pins, terrestrial laser scanning, close-range photogrammetry and rapid visual assessment. Each method has differing temporal and spatial limitations that affect its suitability for assessing the severity and extent of post-fire erosion.

Water sampling in reservoirs

Analysis of water samples provides data on sediment loads and the differences in certain chemical characteristics between pre and post-fire conditions. Parameters that indicate erosion from within the catchment include suspended solids, total dissolved solids and turbidity. Extensive research into sediment loads following wildfire has been undertaken in water reservoir catchments (Lane *et al.* 2006; Moody and Martin 2001; Smith *et al.* 2011; White *et al.* 2006; Wilkinson *et al.* 2007) and to a lesser extent following prescribed fire (Smith *et al.* 2010) where pre-fire baseline data exists. The accuracy of data derived from water samples relies on the rigorous experimental design and sampling regimes implemented. Water samples do not allow temporal comparisons to be made unless regular and repeated sampling is undertaken. In their review of wildfire effects on water quality in forest catchments Smith *et al*. (2011) provided a comprehensive summary of the potential impact on water supply following wildfire and the directions for future research.

Water samples were collected and analysed for suspended sediment and turbidity from the water reservoir following the Mount Bold wildfire (Fig. 2a and Table 1). Additional sampling sites were added after the fire to assess the sediment load reaching the reservoir. Many of these sites did not have regular pre-fire data. The few sites with reliable pre-fire data indicated minimal disturbance by the wildfire even though substantial sediment movement was measured within the burnt catchment (Morris *et al.* 2008a). These results can be attributed to the already high background levels of turbidity and the limited replication of additional sites within the reservoir. Most of the prescribed burns conducted in the Mount Lofty Ranges are not within catchments with sufficient instrumentation to compare pre-and post-fire sediment loads.

Sediment traps

Sediment traps are designed to capture any sediment passing a given line. Fire researchers have used many different types of traps to measure post-fire erosion such as silt fences (Robichaud 2005; Robichaud and Brown 2002), gerlach troughs (Keizer *et al.* 2005) and concrete aprons with overflowing tanks (Blong *et al.* 1982; Dragovich and Morris 2002; Prosser and Williams 1998) or V-notch weirs (Lane *et al.* 2004). To mitigate post-fire erosion, land managers have installed hay bale traps also known as straw bales (Morris *et al.* 2008a; Robichaud *et al.* 2008), log contour traps (Robichaud *et al.* 2008) and silt fences (Dunkerley *et al.* 2009; Robichaud 2005). All traps are designed to capture sediment whose volume can be measured.

At Mount Bold over 50 traps (Fig. 2b and Table 1) were installed to minimise sediment transfer into the water reservoir (Morris *et al.* 2008a). Trap designs included three varieties made from hay, coir and silt fencing. Sediment volumes were measured using tape measures and shovels. Sediment samples from behind six traps were collected then analysed in the laboratory to determine nutrient content and leaching potential. Many of the traps were insufficient in size and strength to capture all the passing sediment. In hindsight rock gabions may have been a better material to use to prevent trap failure. Limitations of using sediment traps include inadequate design to capture all passing sediment, the expense of installing the number of traps required to undertake adequate statistical analysis, extensive maintenance, interference with the natural processes, and the amount of time taken to install and monitor the traps. The strength of sediment traps are that hydrological properties can be studied simultaneously and that the sediment can be collected and further analysed for chemical content and physical attributes.

Table 1. Equipment, associated cost, weight and field personnel involved in the Mount Lofty Ranges Case study. Cost expressed in Australian dollars (2008).

Technique	**Equipment**	**Estimated average cost**	**Approx.** Field Weight	**Field time to sample (does not include travel time)**	**Field personnel involved**
Reservoir water sampling	boat, jars, laboratory, chemicals	$10 - $300 per sample for lab analysis	500g per sample	5 min*	4
Sediment trapping-hay bales	hay bales, star pickets, jute matting, hammers, shovels	$170 per average sized trap	50kg per trap	30 min	28
Stratigraphy	sample bags, shovel, ruler	$20 for all sites	5kg plus sediment samples	30 min for one small trench	4
OSL dating	sample tubes, sample bags, dating machines, scintillation counter	$1000-$1500 per sample for lab analysis	15kg plus sediment samples	30 min*	2
Radiocarbon dating	sample bags, dating machine	$500-$700 per sample for lab analysis	5kg plus sediment samples	10 min*	2
Erosion pins	metal pins, hammers, rulers	$4 per pin	70g per pin	20 min	2
Terrestrial laser scanner	laser scanner, GPS	$240 000 for scanner, computer and software	20kg	20 min*	3
Close-range photogrammetry	field tripods, cameras, survey equipment, numerous personnel	$25 000 for cameras, tripod, survey equipment computer and software	20kg	60 min*	4
Visual assessment	GPS, clipboard, clinometer, water dropper	$60 for clinometer, water dropper, clipboard and bag	500g	5 min	1

* Although field time may appear minimal there is substantial time spent either in the laboratory or processing computer data.

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Fig. 2. Field set-ups and associated equipment for assessing onsite natural post-fire soil erosion.

A) *Water sampling* B) *Sediment traps* C) *Stratigraphy* D) *Dating: OSL dating* E) *Erosion pins* F) *Terrestrial laser scanning* G) *Close-range photogrammetry* H) *Visual assessment*

Stratigraphic analysis

Stratigraphy involves the observation and interpretation of fire-related layers within soil or sedimentary profiles. Charcoal-rich sediment provides evidence of past fires. In the Australasian region Mooney *et al*. (2011) compiled 223 sedimentary charcoal records to examine the temporal and spatial variability of fire regimes during the Late Quaternary. Condera *et al.* (2009) highlighted a lack of agreement in defining fire-derived materials, choosing the best extraction procedures, and recognising of the processes involved in their formation and deposition.

In the Mount Lofty Ranges post-fire soil profiles in depositional environments (Fig. 2c and Table 1) were compared to the paleofire sedimentation processes inferred from the exposed peat bog at Cleland (Fig. 2d and Table 1) (Buckman *et al.* 2009). Eroded sites were devoid of charcoal-rich sediment and ash after the wildfire. Radiocarbon and OSL (optically stimulated luminescence) dating (Fig. 2d, Table 1) at the Cleland stratigraphic section has enabled the sedimentary sequences to be interpreted in relation to depositional environments. Over a period of approximately 6000 years there were at least fifteen separate fire events that caused post-fire deposition (Buckman *et al*. 2009). Soil profiles exposed from digging trenches after the 2007 Mount Bold wildfire also provided clear evidence of a charcoal-rich layer of sediment being deposited over the pre-fire soil profile and sediments. Stratigraphy therefore has potential for assessing both the short and long term effects of conducting frequent burns.

Erosion pins

Erosion pins provide a fixed position from which differences in ground surface change can be measured. A metal rod is hammered vertically into the ground, then either rulers or calipers are used to measure the distance between the top of the pin to the mineral earth surface. Erosion pins are generally installed in a grid pattern or along transect lines. A temporal comparison is possible as the pins remain relatively fixed at a given point within the landscape. In the post-fire landscape erosion pins have been used to monitor hillslope erosion in temperate forests (Mackay *et al.* 1984) and alpine areas in NSW, Australia (Smith and Dragovich 2008), monsoonal savannah woodlands in NT, Australia (Russell-Smith *et al.* 2006), moorlands in Yorkshire, UK (Imeson 1971) and pine forest in Mexico (White and Wells 1979).

In the Mount Lofty Ranges erosion pins (Fig. 2e and Table 1) were used to monitor surface level changes at two prescribed fires and the Mount Bold wildfire. At the prescribed fire locations a Before–After–Control–Impact (BACI) experimental design was implemented. A BACI design is not possible at the wildfire site due to pins not being installed prior to the fire. Limitations of using erosion pins included surface disturbance, trapping of sediment by the pin and limited spatial coverage due to the time-consuming nature of both installing and measuring each individual pin. Other sources of erosion pin data contamination are discussed by Haigh (1977). Erosion pins do not provide details on the hydrological processes associated with sediment movement or on sediment transfer beyond the pin grid. The strength of the erosion pin data in the Mount Lofty Ranges is the monitoring of a relatively fixed point location over a 2 to 3 year timeframe with potential for future readings if the pins remain installed.

Laser scanning

Terrestrial laser scanners (TLS) use laser beams to survey topography. Data generated by the survey can be collected over repeated timeframes allowing for comparisons of digital elevation data. Erosion and deposition have been quantified by using digital elevation models (Hancock *et al.* 2008; O'Neal and Pizzuto 2011). In the post-fire environment Martin *et al.*(2008) used terrestrial laser scanning to represent depression storage of sediment and Canfield *et al.* (2005) used aerial laser scanning to validate erosion models.

After the wildfire at Mount Bold, TLS was successfully trialled over two different dates to create a digital elevation model of surface elevation change. The survey was conducted using a Maptek I-Site 4400LR terrestrial laser scanner (Fig. 2f and Table 1). This TLS is a time of flight pulsed rangefinder. It has a range of up to 700 m depending on reflectivity with a typical range accuracy of 50 mm under general scanning conditions from 5 to 700 m. The scanner measures 4400 points per second. Scanning was conducted at numerous locations to reduce shadow effects by maximising scan angle across surfaces and to create scan overlap. At Mount Bold the TLS enabled measurement of surface elevation changes to be made on slopes that were previously inaccessible due to steep (greater than 45 degrees) unstable slopes.

Limitations with the TLS included the inability to measure through dense vegetation regrowth that occurred after 6 months and the technical knowledge required to operate the scanner and process the data. Operators need to be aware of the field operation of the equipment, terrain characteristics and instrument specifications to ensure accurate data is obtained (Heritage and Hetherington 2007). The strength of TLS as applied by the authors is its spatial coverage, ability to measure surface changes exceeding ±50 mm (magnitude), rapid data collection and a scanner that does not interfere with the hydrology or geomorphology at the measured site.

Digital close-range photogrammetry

Photogrammetry measures changes in the surface elevation by capturing overlapping images and applying morphometric survey techniques. Recent technological advances have made the use of digital close-range photogrammetry a viable option for measuring post-fire erosion. In laboratory and field conditions the use of this method is proving to be highly valuable (Gessesse *et al.* 2010; Rieke-Zapp and Nearing 2005). To date digital close-range photogrammetry has not been used in the post-fire environment to measure surface change.

Digital close-range photogrammetry was trialled at the Cleland prescribed burn in the Mount Lofty Ranges (Fig. 2g and Table 1) to measure the subtle changes in surface elevation between rainfall events following prescribed fire (Morris *et al.* 2008b). Success was limited at Cleland due to the developmental stage of the technique in the field (±6mm vertical scale accuracy compared with the capability of ±1mm). Limitations of close-range photogrammetry for operational management include a minimum of two personnel to carry and erect the equipment, the technical knowledge required to process the captured images and the early development stage of the technique. Spatial coverage and replication is limited by the time it takes both to carry and set-up the equipment. Close-range photogrammetry warrants further investigation due to the potential information it can provide on the movement of soil involved in micro-topography such as litter dams and micro-terraces, which retain soil and prevent potential excessive loss of sediment.

Visual assessment

Visual assessment involves describing and/or measuring the geomorphological features associated with sediment movement. Shakesby *et al.* (2003) described and measured ground surface changes including rock cover, newly deposited sediment, faunal activity, litter dam heights, soil pedastools and exposed roots after the Sydney 2001 wildfires. Ruiz-Gallardo *et al.*(2004) applied field erosion assessment to test the reliability of their forest intervention priority map and Berg and Azuma (2010) quantified observations of bare ground and rills to examine erosion recovery following fire. To date there has been no consistent framework for rapid and relatively easy assessment that can be carried out by both researchers and land management agencies.

A descriptive framework (Fig 3) was applied in the Mount Lofty Ranges to assess post-fire sediment movement based on the morphological runoff zones identified by Bracken and Kirkby (2005). This framework is designed to rapidly assess post-fire sediment movement so that researchers can obtain large representative sample numbers and land management field staff can readily and economically assess post-fire erosion. Sampling designs can incorporate the heterogeneous nature of the landscape due to the limited field time required. The framework incorporates ground surface features including splash pedestals, litter dams, small deposit features and debris flows recorded in other post-fire erosion studies (Nyman *et al.* 2011; Shakesby *et al.* 2003).

In the Mount Lofty Ranges case study 505 sites were assessed using the framework in relation to the 10 prescribed burns (Fig. 2h and Table 1). Control sites were included by applying the framework in adjoining unburnt areas. Field assessment was conducted using transects lines that ran both parallel and perpendicular to the contour for eight of the prescribed burn locations. Rapid assessment allowed a relatively unbiased assessment on whether the prescribed burning resulted in minimal sediment movement. Quantifiable results were included by measuring the depth of ground surface features. Differing magnitudes of erosion events were easily recorded and described. The framework enabled large areas to be assessed with adequate replication and spatial representation due to the freedom of not carrying heavy, expensive and bulky equipment as required in many of the methods (Fig 2, Table 1). Land management agencies can easily apply this framework in the field after minimal training.

Timeframes, spatial scales, magnitude and frequency

Selection of the appropriate method to assess post-fire erosion requires a combination of the land management priorities underlying the work, the spatial scale at which land management operations are conducted and the temporal scale at which the threat is assessed. Erosion in the post-fire landscape varies in scale and magnitude. To provide a framework for interpreting disturbance regimes such as erosion, Miller *et al*. (2003) and Benda and Dunne (1997a; 1997b) discuss three concepts including a spatial template, stochastic temporal driver and an antecedent sequence of events. After prescribed burning the magnitude of erosion tends to be low to moderate (Coelho *et al.* 2004) and the fire perimeter is within a known spatial scale. After wildfires the magnitude is highly variable depending on antecedent conditions (Pierson *et al.* 2002), fire severity (Chafer 2008; Godson and Stednick 2010; Prosser and Williams 1998; Shakesby 2010), timeframe (Tomkins *et al.* 2007) and the intensity of subsequent rainfall (Tomkins *et al.* 2008). In Table 2 the effectiveness of post-fire erosion assessment methods used in the Mount Lofty Ranges are outlined in the context of timeframes, spatial scale, magnitude and frequency.

In the Mount Lofty Ranges no one method was able to successfully assess sediment movement for extended timeframes over large spatial scales, covering all event magnitudes (Table 2). In the case of prescribed burning, the timeframe for assessment is usually within the first year, over a scale varying from plot to catchment, with an event magnitude of low to high. If land managers wanted to assess low magnitude erosional events, then the ideal methods would be visual analysis, stratigraphy or close-range photogrammetry. If the event magnitude was greater than high it would be advisable to replace close-range photogrammetry with terrestrial laser scanning as it measures features greater than 50 mm. If the prescribed burn covered large areas such as hillslopes or entire catchments, the use of sediment traps or water sampling may also be appropriate.

Sediment Class	Types of Evidence	Examples
1	Surface crusting Armouring Splash pedestals * Small areas of wash deposits	
2	Depositional steps (<10 cm^2) (often behind vegetation) Litter dams and micro-terraces * Larger areas of wash deposits (<50 cm^2)	
3	Some concentrated flow Erosional steps/small headcuts Deposition >10 cm * Colluvial fans <1 m deep Drainage scouring >10 mm	
4	Concentrated rills (cross-sections >0.1m^2) * Colluvial fans ≥1 m deep Debris flows <1 m wide	
5	Gullies (>1 m deep) with own side slopes Colluvial fans >5 m deep Debris flows >1 m wide *	

Fig. 3. Rapid visual post-fire erosion assessment framework. Modified from Bracken and Kirkby (2005) and Kirkby *et al.* (2005). A sixth category could be included for major landslides, debris flows and/or multiple gully developments. For this study in the Mount Lofty Ranges a sixth class was not required. *Image located to the right.

Table 2. Summary of the effectiveness of post-fire erosion assessment methods used in the Mount Lofty Ranges in the context of timeframes, spatial scale, magnitude and frequency.

Method	Event timeframe				Event spatial scale					Event magnitude					Frequency
	Short (<1yr)	Medium (>1<10yrs)	Long (>10 <100yrs)	Historical (>100)	Point (mm)	Plot (m^2)	Hillslope (m^2 to km^2)	Catchment (km^2)	Landscape (>km^2)	Low	Moderate	High	Very High	Extreme	
Water samples	Y	Y	Y	N	Y	N^*	N^*	Y	N^L	N	N	N^*	Y	Y	Y
Sediment traps	Y	N^*	N	N	N	Y	Y	N^L	N	Y	Y	Y	N^*	N^*	N^*
Stratigraphy	Y	Y	Y	Y	Y	Y	N^L	N^L	N^L	Y	Y	Y	Y	Y	Y
Dating	N^*	N^*	Y	Y	Y	N^L	N^L	N^L	N^L	N^*	N^*	Y	Y	Y	Y
Erosion pins	Y	Y	N^*	N	Y	N^L	N^L	N^L	N	Y	Y	Y	N^*	N^*	N^*
Laser scanning	Y	N^*	N^*	N	Y	Y	Y	N^L	N^L	N^*	Y	Y	Y	Y	N^*
Close-range photogrammetry	Y	N	N	N	Y	Y	N^L	N	N	Y	Y	Y	N^*	N^*	N^*
Visual assessment	Y	Y	N^*	N	Y	Y	Y	N^*	N	Y	Y	Y	Y	Y	N

Y = Yes, method is suitable

N = No, method is not suitable

N^* = If the materials or experimental designs were modified it would be possible to use this method.

N^L = Point or small areas can be interpreted and extrapolated to larger areas.

Conclusion

In this case study of assessing post-fire erosion in the Mount Lofty Ranges, the authors applied and compared different techniques to assess erosion. It was found that for operational use a simple rapid visual assessment framework provides an affordable approach that is time efficient compared to other methods. With minimal training land management operational staff could audit environmental assessments in relation to erosion from prescribed burning. Researchers would also benefit from using this framework due to the minimal cost and field time. Spatial variability within the landscape could be incorporated into the research due to the large datasets that can be easily complied using the framework.

Selecting the appropriate erosion assessment methods depends on land management priorities and the capability of the assessment. Historical erosion is best recorded using stratigraphy and dating to measure sediment characteristics, depth and age. Stratigraphy also provides details about the frequency of deposition, allowing comparison between current burning regimes with those in the past. Morphometric methods, including terrestrial laser scanning and close-range photogrammetry, have improved our ability to measure sediment movement over a variety of scales. These results can then be interpreted to assist in understanding micro-topography, catchment and landscape scale processes. The ideal assessment of post-fire erosion would use a combination of monitoring methods to cover all timeframes, spatial scales, event magnitudes and frequency.

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Chapter 3: Soil erosion following prescribed burning

Two weeks after the prescribed burn at Kangaroo Gully in Scott Creek conservation reserve.

Chapter 3 is a manuscript that was submitted to the International Journal of Wildland Fire on 19 January 2013 as:

Morris RH, Bradstock RA, Dragovich D, Henderson K, Penman TD, Ostendorf B (submitted) Environmental assessment of erosion following prescribed burning in the Mount Lofty Ranges, Australia. *International Journal of Wildland Fire*

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3.2 Statement of contribution

As primary author I was responsible for the conceptualisation of the work by developing the erosion assessment framework, the spatial field sampling design and liaising with the relevant land management agencies including DEWNR, SA Water and the Botanic Gardens. In relation to the study realisation I completed all field work, data entry and was involved in the statistical analysis using R programming. I prepared the initial manuscript and incorporated the suggestions by the other authors. The role of D Dragovich, B Ostendorf and M Henderson was advice on the research conceptualisation, data analysis and editing of the manuscript. B Ostendorf also advised on the incorporation of a spatial field sampling design. R Bradstock provided advice on data analysis, interpretation and editing of the manuscript. T Penman provided statistical advice about generalised additive models and the program R. T Penman also provided editorial comments on the manuscript.

I hereby certify that the statement of contribution is correct.

____________________________R Morris (Candidate) 23/1/13 Date

I hereby certify that the statement of contribution is correct and I give permission for the inclusion of the paper in the thesis.

____________________________R Bradstock 1/2/13 Date

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M Henderson 24 JAN 2013 Date

____________________________T Penman 8/2/13 Date

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Environmental assessment of erosion following prescribed burning in the Mount Lofty Ranges, Australia

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Abstract. Erosion following fire has the potential to impact on water quality, alter soil profiles and cause detrimental impacts to human infrastructure. There is a clear need for environmental assessments to have regard for erosion concerns from prescribed burning. This study focusses on ten prescribed burns conducted in the Southern Mount Lofty Ranges. Generalised additive modelling is used to determine the main significant environmental variables influencing the presence of sediment movement at 505 field-assessed sites. Sediment movement after the ten prescribed burns was minor. Fire severity was a highly significant environmental determinant for the presence of sediment movement after prescribed burning. To identify erosion concerns a suite of environmental variables is more reliable than focusing solely on slope steepness, as occurred prior to this study. These results indicate that erosion assessments need to consider a range of environmental influences and that land managers and scientists need to incorporate spatial sampling designs into erosion assessments.

Additional keywords: erosion assessment, slope, fire severity, rainfall, topography, bioturbation, sediment movement

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Introduction

Post-fire soil erosion is a concern due to the potential adverse effects on water quality, the alteration to soil profiles and the detrimental impacts on human communities. Water reservoirs have been decommissioned due to poor water quality following major wildfires

(Smith *et al*. 2011; White *et al*. 2006). Fire can alter soil properties and cause redistribution of sediment within the hillslope resulting in changes to the existing soil profile (Certini 2005; Shakesby and Doerr 2006). Post-fire soil erosion, especially debris flows, create a risk to human life and infrastructure (Cannon and Reneau 2000; Nyman *et al*. 2011). Erosion problems following prescribed fire (the intentional use of fire to achieve specific objectives) are less common than those studied following wildfire; however the risk is still present as evident by the debris flow example provided by Cawson *et al*. (2012).

A wide variety of environmental variables influences the rates and extent of post-fire erosion (Bento-Gonçalves *et al.* 2012; Shakesby 2010; Shakesby and Doerr 2006; Shakesby *et al.* 2007). Fires of high severity remove substantial vegetation cover, therefore exposing soil to rainfall and overland flow (Cerda and Doerr 2005; Robichaud and Waldrop 1994). The duration and length of rainfall post-fire influences the amount of water and its associated erosive processes (Inbar *et al.* 1998; Moody and Martin 2001a; Prosser and Williams 1998). Steeper slope gradients and longer slope lengths increase sediment movement (Smith and Dragovich 2008; Wright *et al.* 1976). Drainage patterns and connectivity (Kirkby *et al.* 2005; Moody *et al.* 2008) govern water flow characteristics that subsequently transport the eroded material from the burnt sites. Soil properties alter the sediment grain dispersal characteristics (Certini 2005). Bioturbation influences infiltration (Shakesby *et al.* 2006) and bio-transfer (Cerda and Doerr 2009; Dragovich and Morris 2002a; Richards *et al.* 2011). Restoration strategies and mitigation also have the ability to influence post-fire erosion (Cerda and Robichaud 2009).

Predicting post-fire erosion effects is difficult due to the wide variety of variables and the complex interactions that result in differing magnitudes of soil erosion (Benavides-Solorio and MacDonald 2005). Extensive work in the US has been completed to develop a suit of management ‘tools’ designed to assist land managers with work in the post-wildfire environment (Robichaud and Ashmun 2012). Assessing post-fire erosion concerns in Australia could be enhanced by trialling and adopting similar methods.

Within Australia each State has its own system for assessment of erosion potential. For example in New South Wales a code has been developed to streamline environmental approval for hazard reduction works (Brompton *et al.* 2006). In NSW, if a soil erosion risk map does not exist, moderate or higher intensity prescribed fires are not to be applied to slopes steeper than 18 degrees. In South Australia managers use conceptual models in relation to predicting potential erosion and are currently in the process of developing various new written guidelines. Previous environmental reviews (Table 1) have mainly focused on slope steepness in relation to erosion concerns after prescribed burning.

Given that many variables may influence post-fire erosion it is questionable whether a threshold slope of 18 degrees (slope gradient 1:3) is the only variable that needs to be considered for assessments. In order for land managers to successfully assess and predict erosion potential there is a need for an environmental assessment that encompasses the main variables that influence post-fire erosion. In this study, erosion following prescribed burning was assessed in managed reserves located in South Australia. The objectives of this study were to (1) assess if prescribed burning increased the amount of sediment movement in the Southern Mount Lofty Ranges; (2) model the probability of sediment movement occurring following prescribed fire in the Southern Mount Lofty Ranges; and (3) to determine the influence of slope on post-fire erosion.

Table 1. Excerpts in relation to erosion from the unpublished Part A environmental assessment tables completed to meet provisions under the South Australian *Native Vegetation Act 1991*

Burn Name Reserve	Land Manager	Consideration	Potential impacts
Belair S09	DEWNR	Potential to alter erosion potential, particularly in areas with steep slopes (>18º)	Slopes typically less than 18º. No impact predicted.
Berri Werri	DEWNR	Potential to alter erosion potential, particularly in areas with steep slopes (>18º)	While slopes within the burn site are between 20 - 30º, erosion is likely to be minimal due to the mosaic and small size of the burn
Cleland S09b	DEWNR	Potential to alter erosion potential, particularly in areas with steep slopes (>18º)	The burn site consists of moderate slopes. There is the potential for erosion, particularly in drainage lines. A low intensity burn allows much of the flora, particularly the resprouters, to re-establish cover rapidly after burning which will help mitigate erosion.
Gate 17	DEWNR	Potential to alter erosion potential, particularly in areas with steep slopes (>18º)	Slopes typically less than 18º. No impact predicted.
Kangaroo Gully	DEWNR	Potential to alter erosion potential, particularly in areas with steep slopes (>18º)	Slopes on the site are generally less than <18 º. Erosion is likely to be minimised due to the mosaic and low intensity prescription of burn.
Mount Lofty S09	Botanic Gardens	Potential to alter erosion potential, particularly in areas with steep slopes (>18º)	There is unlikely to be any erosion on this site due to its gentle slope <20º
Warren	SA Water	The proposed burn area is on a 5º - 10º slope on acidic gradational sandy loam on rock with high erosion potential.	Depending on the intensity of the burn there may be some erosion in places.
Wildlife	DEWNR	Potential to alter erosion potential, particularly in areas with steep slopes (>18º)	Site is along a ridge line with lower sections recording slopes of up to 20º. Erosion should be minimised due to the mosaic and low intensity prescription of burn.
Wottons Scrub	DEWNR	Potential to alter erosion potential, particularly in areas with steep slopes (>18º)	Erosion will be minimized due to the mosaic and low intensity prescription of burn. Large fallen timber, remaining unburnt material and regenerating vegetation will slow runoff and reduce erosion potential of steeper slopes
Mylor S09	DEWNR	Potential to alter erosion potential, particularly in areas with steep slopes (>18º)	Erosion potential is low due to the gentle slopes at the burn site and the small size of the burn.

Study area

The study area (Fig. 1) is located in the Southern Mount Lofty Ranges to the east of Adelaide (35°07’S,138°41’E) in a temperate Mediterranean-climate zone, with warm to hot, dry summers and mild to cool wet winters. The Southern Mount Lofty Ranges are composed of deformed Proterozoic and Cambrian sedimentary rocks of the Adelaide Fold Belt which include quartzite, shale, dolomite, sandstone and conglomerate lithologies (Daily *et al.* 1976; GSAA 1962). Soils formed from these rocks are mainly shallow to moderately deep acidic soils (Soil and Land Program 2007). Soils in the study region are susceptible to erosion with a total of approximately 40% of the area having erosion rates of above 1 t/ha/y in unburnt conditions (Wilkinson *et al.* 2005). The topography is dissected by small tributaries that feed into the Gawler, Torrens and Onkaparinga Rivers (Fig. 1) and over ten percent of the study area has slope angles greater than 18 degrees. Native vegetation consists predominantly of dry *Eucalypt* forests and woodlands with either grassy or shrubby understoreys (Armstrong *et al.* 2003).

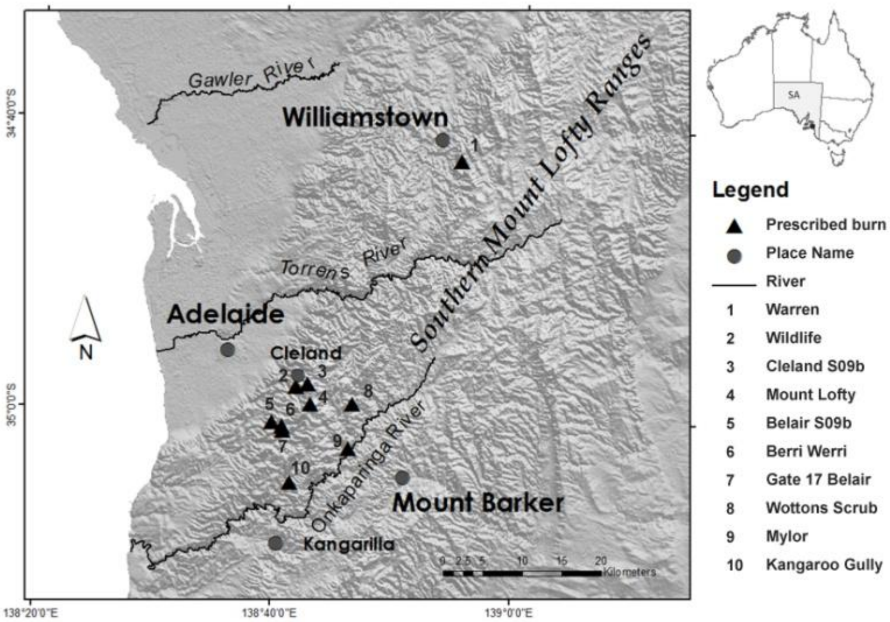

Fig. 1. Location of the prescribed burn study sites in the Southern Mount Lofty Ranges, South Australia. Prescribed burns are represented as black triangles. (Digital Elevation Model sourced from Shuttle radar topography mission data).

Annual rainfall during the study period at Mount Lofty Botanic Gardens, (Australian Bureau of Meteorology station ID 023788: 34.98° S 138.72° E; elevation 510 m) was 1112 mm in 2007, 1016 mm in 2008, and 1280 mm in 2009. Between 2007 and 2009, 78% of the combined monthly rainfall was recorded between the months of April to September.

Wildfires have influenced land formation in the study area over thousands of years (Bickford and Gell 2005; Buckman *et al.* 2009). Wildfires such as 'Ash Wednesday'1983 burnt over 200 000 ha (Healey *et al.*, 1985). In the study area 186 wildfires burning 10 500 ha have been recorded between July 2001 and June 2010 (Department of Environment, Water and Natural Resources -DEWNR-Fire History database). Local fire authorities have increasingly been using prescribed burning to reduce fuel loads in order to minimise the intensity and rate of spread of wildfires.

Methods

Spatial field sampling design

The study uses ten prescribed burns located within the Southern Mount Lofty Ranges (Fig 1, Table 1, 2) that were part of the annual fuel reduction program during 2007 to 2009. Prescribed burns ranged in size from 1 to 58 ha with an average area of 14 ha. Fire severity varied both within and between the burns ranging from low (ground fuels and low shrubs burnt) to very high (ground fuels and lower shrubs burnt; upper canopy consumed). Four of the burns contained patchy unburnt sections within the burn perimeter.

Erosion assessments were made for a total of 505 sites at regular intervals along linear transects within the ten burns. Transects were selected to run parallel and perpendicular to the hillslope in order to include samples from ridgetop to drainage lines as well as to include variability within hillslope positions such as wash deposits and surface bioturbation. The interval between transect lines and points on most lines was 10 or 20 m depending on the size of the prescribed burns. Only one burn ('Wildlife', Fig. 1) was sampled at a larger, 500 m by 50 m line/point spacing. Where possible, transects cover both unburned and burned areas. Of the 505 sites assessed 342 sites were within the prescribed burns and 163 control sites adjoined the burns.

Table 2. Study sites characteristics

DEWNR, Department of Environment, Water and Natural Resources

Burn Name Reserve Department	Days between burn and assessment	Total rainfall (mm)	Vegetation [A]	Soil [B] Group	Water [B] erosion potential	Number of erosion assessments	Burn size (ha)
Belair S09 BELAIR DEWNR	74	37.4	SM0101 SM2401 SM2601	K2, K5	5,6	60	3
Berri Werri BELAIR DEWNR	24	35.2	SM0101 SM1201	F1, L1	3,6	22	1
Cleland S09b Cleland DEWNR	214	688.9	SM0101 SM0201	K1, K5	6	99	10
Gate 17, Belair Belair DEWNR	137	488.8	SM0101	K5, L1	5,6	51	3
Kangaroo Gully Scott Creek DEWNR	11	126	SM2702	K4	6	35	58
Mount Lofty S09 Botanic Gardens	99	121.8	SM0101	K5	6	25	3
Mylor S09 Mylor DEWNR	48	32	SM0101	K4	5	75	3
Warren Warren SA Water	87	108	SM0901	K4, K5	5	86	25
Wildlife Cleland DEWNR	122	225.6	SM0101	K5	6	10	26
Wottons Scrub Kenneth Stirling DEWNR	35	57	SM0201	K4	5	42	6

[A] Vegetation units from the Department of Environment, Water and Natural Resources floristic database (Armstrong *et al.* 2003)

[B] Soil community group and water erosion potential from the Land and Soil Spatial Data for South Australia (Soil and Land Program 2007)

Erosion assessment and environmental variables

Erosion assessment was based on a framework of sediment movement classes described by Morris *et al.* (2011) (Table 3). At each of the 505 sites a circular area with a 1.5 m diameter was classified into one of six erosion categories ranging from 0 to 5. At each assessment site any erosion or deposition was recorded noting the type of erosion features (Fig. 2). Any obvious erosion or deposition depths were measured. A perimeter inspection was conducted at each burn to determine if any sediment had left the burn boundary.

Table 3. Rapid visual post-fire erosion assessment framework

Modified from Morris *et al*. (2011), Bracken and Kirkby (2005) and Kirkby *et al.* (2005). A sixth category could be included for major landslides, large debris flows and/or multiple gully developments. Classes 0 - 3 were required for assessing prescribed burns in the Southern Mount Lofty Ranges.

Sediment Class	Types of evidence
0	No evidence
1	Surface crusting
	Armouring
	Splash pedestals
	Small areas of wash deposits
2	Depositional steps (<10 cm^2) (often behind vegetation)
	Litter dams and micro-terraces
	Larger areas of wash deposits (<50 cm^2)
3	Some concentrated flow
	Erosional steps/small headcuts
	Deposition >10 cm
	Colluvial fans <1 m deep
	Drainage scouring >10 mm
4	Concentrated rills (cross-sections >0.1m^2)
	Colluvial fans ≥1 m deep
	Debris flows <1 m wide
5	Gullies (>1 m deep) with own side slopes
	Colluvial fans >5 m deep
	Debris flows >1 m wide

Fig. 2. Photographic examples of three different sediment movement classes

a) Class 1 Splash pedestals at Belair Gate 17
b) Class 2 Litter dams and micro-terraces at Wotton
c) Class 3 Colluvial charcoal-rich sediment trapped by the fencing at Belair Gate 17
d) Class 3 Alluvial charcoal-rich sediment transported by the drainage system at Kangaroo Gully

Fire severity, rainfall, vegetation, soil properties, bioturbation and topographic data were collated for all sites using field observations or state-wide databases (Table 4). We adopted the fire severity classification of Chafer *et al.* (2004) for *Eucalyptus* forests and woodlands ranging from extreme (all green vegetation burnt and stems <10 mm thick incinerated) to low (ground fuels and low shrubs burnt). Daily rainfall data were sourced from the nearest operational Australian Bureau of Meteorology Automatic Weather Station or from the local rainfall data recorded at Mount Bold. Rainfall intensity average recurrence intervals were interpolated by the Australian Bureau of Meteorology. Total rainfall and days of rainfall greater than 5 mm were also considered.

Table 4. Variables used in the analysis of predicting the probability of sediment movement occurring

Variable	Anticipated effect	Data source, type and spatial scale (burn or site specific)
Fire severity [A]	Increasing fire severity removes vegetation cover and alters soil properties exposing the soil to erosive processes	Field-classified categories including unburnt, moderate, high, very high and extreme. Site specific.
Rainfall [A]	The duration and intensity of rainfall influences the amount of runoff and its associated erosive processes	Bureau of Meteorology station data including total rainfall and mm/ day. Burn specific.
Aspect relative to NW [A]	Aspect influences the amount of radiative forcing that the land surface receives, enhancing or deterring soil dryness and vegetation growth rates	Field measurement using a magnetic compass. Site specific.
Bioturbation [A]	Bioturbation influences water infiltration and bio-transfer	Field observation of % cover and type. Site specific
Slope degree [A]	Steeper slopes influence water velocity leading to increased erosive processes; and influence the force of gravity	Field measurement using a clinometer. Site specific.
Slope length [A]	Longer slopes increase water velocity leading to increased erosive processes	Measurement of distance using a 1:50000 map. Site specific.
Hillslope [A] position	Position along the hillslope. Influences water runoff and connectivity	Field-classified categories including ridge, upper, mid, lower, drainage. Site specific.
Cross-slope curvature [A]	Influences drainage patterns and the connectivity that govern water flow characteristics	Field-classified categories including concave, convex, planar. Site specific.
Vegetation type	Different vegetation structures vary in how they bind soils and intercept rainfall	GIS data: DEWNR floristic mapping. Site specific.
Vegetation cover	Increased vegetation cover provides increased protection and binding of the soil surface	Field-assessed cover and height for litter, near surface, understorey, canopy.
Vegetation consumed	Decreasing vegetation cover decreases soil surface binding and protection	Field-assessed consumption of litter, near surface, understorey, canopy.
Hydrophobicity	Increased hydrophobicity decreases infiltration leading to increased overland flow	Field measurement using a water penetration test. Site specific.
Soil type	Soil properties alter the sediment grain dispersal characteristics	GIS data: Soil and land program soil mapping. Site specific.
Water erosion potential	Higher water erosion potential is likely to result in greater erosion due to steeper slope degrees and dispersive soils	GIS data: Soil and land program: modelled using slope and soil types. Site specific.

[A] Variables used in the generalised additive models. Other variable were removed either due to multi-collinearity (Table 5) or field complications (hydrophobicity).

Vegetation types were derived using the DEWNR floristic database (Armstrong *et al.* 2003). Field assessment of vegetation cover included ground, near surface, understorey and crown. Soil types and water erosion potential were derived using the land and soil spatial data for southern South Australia (Soil and Land Program 2007). The water erosion potential is a combination of slope and erodibility of soil landscape map units. Measurement of hydrophobicity was conducted in the field using a simple water penetration drop test over 5 seconds to determine presence or absence (Doerr *et al.* 2004). Hydrophobicity data were not included in the statistical analysis due to wet field conditions at 168 of the 505 sites. The presence of bioturbation in the surface soil layers were recorded including the type and percentage cover. Topographic features were recorded in the field for most assessments. Slope angles were surveyed using a clinometer. Cross-slope curvatures were classified into convex, concave and planar. Slope lengths were measured using a 1:50 000 contour map. Two measurements of slope length were made, the first to the burn perimeter and the second to the top of the water divide. Aspects were recorded using a magnetic compass.

Statistical modelling

Several variables were removed to avoid the effects of multi-collinearity. Correlations between all numerical predictor variables were compared using a Spearman rank correlation. Correlations above 0.5 were removed to avoid the effects of multi-collinearity (Chatterjee *et al.* 2000). These variables included vegetation assessments that correlated with fire severity, rainfall variables that correlated with total rainfall and water erosion potential that correlated with slope degree (Table 5). Consequently the analysis was reduced to a maximum of nine variables: fire severity, rainfall, slope degree, slope length, aspect, bioturbation cover, canopy cover, cross-slope curvature, and hillslope position (Table 5 and 6).

Table 5. Correlations between the removed and retained numerical variables

All *P*-values were <0.001

Retained variables	Removed variables	R value
Total rainfall	Rainfall >30 mm	0.91
	Rainfall >20 mm	0.97
	Rainfall >10 mm	0.95
	Rainfall >5 mm	0.95
Fire severity	Litter consumed	0.86
	Near surface consumed	0.85
	Shrub consumed	0.86
	Canopy consumed	0.52
	Bark char height	0.82
	Litter cover	0.68
	Litter depth	0.65
	Near surface cover	0.68
	Understorey cover	0.52
	Bare ground	0.71
Slope degree	Water erosion potential	0.64
Fire perimeter slope length	Slope length	0.64

Table 6. Spearman Rank correlations in the predictor variables. Upper right triangles are the *P*-value and the lower left triangle represents the *R* statistic.

FS, fire severity; SD, slope degree; SL, slope length to fire perimeter; AN, aspect relative to NW; TR, total rainfall; B, bioturbation cover; C, canopy cover

	FS	SD	SL	AN	TR	B	C
FS		0.153726	<0.001	<0.001	<0.001	0.02269	<0.001
SD	0.063571		0.64886	0.008938	<0.001	0.301842	<0.001
SL	0.164035	-0.02031		<0.001	<0.001	0.238127	0.000514
AN	0.381245	0.116233	0.151233		0.322118	0.010005	0.000711
TR	0.230560	0.495324	-0.206800	0.044147		<0.001	<0.001
B	0.101387	0.046035	0.052589	-0.114520	0.148581		0.758052
C	-0.25969	0.497909	-0.154030	-0.150150	0.233850	-0.01374	

To fulfil the assumptions of the statistical methodologies data were transformed prior to analysis. The dependant variables were transformed to a binary classification (i.e. presence or absence of sediment movement). A binary classification was used due to the minimal count of data in the sediment classes (Table 3) that were higher than category 2. Slope length, total rainfall and bioturbation cover were log-transformed before modelling to approximate a normal distribution. Aspects were transformed into degrees relative to north-west because these aspects receive the highest amount of radiation during the hottest part of the day.

Generalized additive models (GAM) were generated to examine different possible combinations of the selected predictor variables using the mgcv package in R (Wood 2006). We used GAMs as they allow for non-linear relationships by generating a smoothing function through the data (Zuur *et al.* 2009). All smoothing functions were limited to three knots, i.e. effective degrees of freedom, to avoid over-fitting of the data. Variables included in the model were classified as highly significant if $P < 0.001$, significant $0.01 < P < 0.05$, marginal $0.05 < P < 0.1$, and not significant if $P > 0.1$. Marginal effects represent the situation where the variable is not classically significant ($P < 0.05$) but there is a statistically meaningful trend that warrants inclusion in the model.

An information theoretic approach was adopted whereby we evaluated all permutations of the nine independent variables (511 models). The best set of models was identified using Akaike's Information Criterion (AIC) (Akaike 1973) selecting only those models with 2 AIC points off the best model. Model fit was measured using the Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC) curve, where a measure of 0.5 represents an entirely random model, 0.7-0.8 fair, 0.8-0.9 good and above 0.9 excellent (Thuiller *et al.* 2003). AUC was calculated using the pROC package (Robin *et al.* 2011). A further management model was tested that is based on the variables of the existing environmental assessments: slope degree, fire severity, total rainfall, fire perimeter, and slope length (Table 1).

Results

Erosion assessment of the prescribed burns

Sediment classes (Table 3, Fig. 2) were easily distinguished in the field with the most common observation being splash pedestals (Class 1). Sediment movement occurred at over half the prescribed burn sites with 40% of the sample being classified into Class 1 (Fig. 3). Only 3% was classified into Class 3 and no Class 4 events were present. At the unburnt control sites sediment movement occurred at only 4% of the sites, compared to the prescribed burnt sites where 52% of the sites had visible movement (Fig. 3). At the control sites only 1% of the samples assessed were equal or higher than Class 2 whereas the burnt sites had 11%.

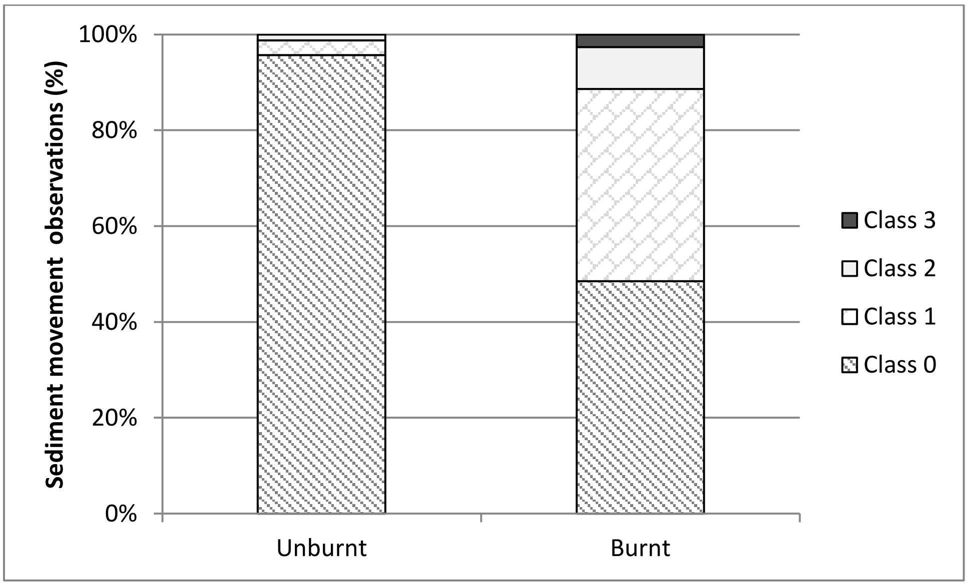

Fig. 3. Comparison of sediment movement observations for unburnt and burnt sites. Sediment movement classes are expressed as a percentage of the total number of observation for either burnt or unburnt sites.
Total observation n=505. (Burnt n=163; Unburnt n=342)

Field observations at all prescribed burns recorded small sediment movement (Fig. 4). Where sediment movements were recorded it involved small distances, generally estimated to be less than 100 mm. The most frequent class for all but four of the burns was Class 0 (no movement). At Cleland S09b, Gate 17, Kangaroo and Mylor, Class 1 was the most frequent sediment movement class. No Class 4 or 5 movements were observed. Class 3 only occurred in minor amounts (<12%) at three of the burns: Gate 17, Kangaroo and Warren. Two of the nine Class 3 records were opportunistic observations from within obvious drainage locations.

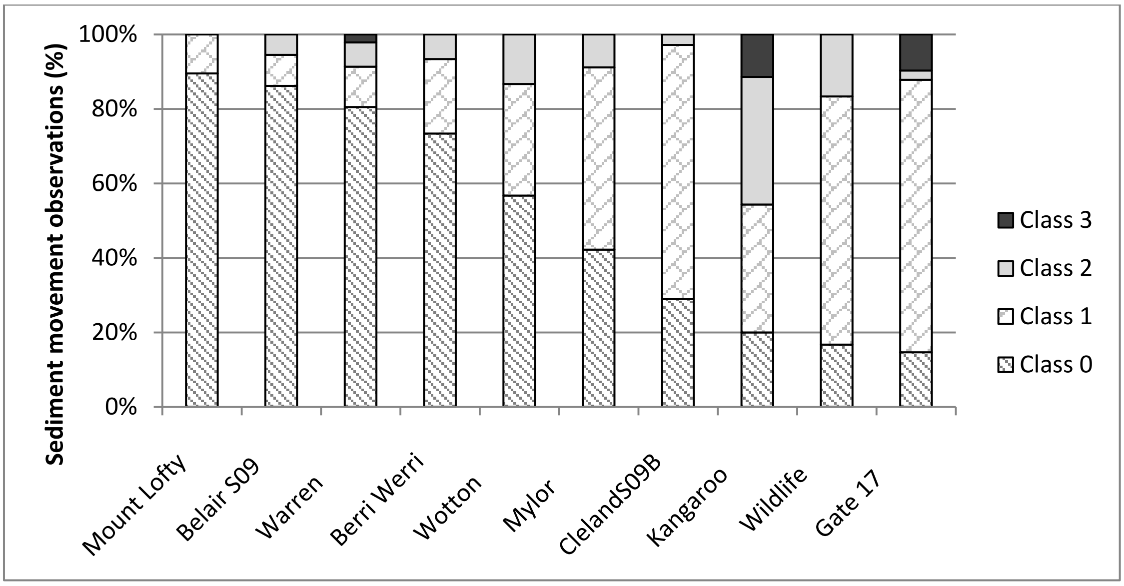

Fig. 4. Comparison of sediment movement observations for each prescribed burn. Sediment movement classes are expressed as a percentage of the total number of observations within the individual prescribed burn.

Perimeter inspections identified sediment washes leaving two prescribed burn boundaries (Gate 17 and Kangaroo). A further two prescribed burns located at Mylor and Wotton had minor amounts of sediment leaving the burn perimeter. The sediment did not appear to travel further than 5 m from the burn sites and any visible evidence of water turbidity downstream from all burns was negligible.

Environmental variables and statistical models

Nine environmental variables were included in the best set of models that predicted the presence of sediment movement (Table 7). Seven alternative models were selected in the best set based on a difference in AIC of 2 (Burnham and Anderson 2002). The best model (Model 1) of the supported set had a good fit and explained 37.3% of the model deviance (Table 7). The detailed response of the critical variables is described below.

Total rainfall was a significant predictor variable in all models (P <0.01). Rainfall has a positive influence on sediment movement if it is higher than approximately 150 mm (Fig. 5a). Confidence bands are relatively narrow over the entire rainfall range. At Cleland S09b the highest total rainfall of 689 mm was recorded between when the fire occurred and the field inspection was conducted. Five burn sites experienced rainfall that was greater than 30 mm over a 24 h period. Mylor had the lowest recorded rainfall totalling 32 mm over 48 days. Class 3 sediment movement only occurred at sites that had been subjected to rainfall that was >20 mm in a 24 h period. Observations of Class 1 movement were higher than Class 0 for areas subjected to daily rainfall of 30 mm or greater. The highest rainfall intensity during the study in 2007 had an average recurrence interval of 1 in 5 years.

Fire severity within the ten prescribed burns ranged from unburnt to very high. In relation to unburnt sites fire severity was a highly significant predictor variable (P <0.001) (Table 7). The probability of sediment movement occurring was more likely in burnt conditions compared to unburnt conditions (Fig. 6). This probability increased by 20% between low to high fire severities depending on the variables included in the model (Fig. 6). There was not a large difference in the probability of sediment movement occurring between high and very high severities.

Table 7. Set of seven best sediment movement occurrence models, alterative management model and the significance for each predictor variable (*P*-value)

FS, fire severity; NW, north-west; FP, fire perimeter; vs, versus; AIC, Akaike's Information Criterion; Δ, Difference from the best model;

*** P <0.001; ** 0.001< P <0.01; *0.01< P <0.05; . <0.05 P <0.1; NS, not significant;

Blank, not included in the model

Model	1	2	3	4	5	6	7	Alt
Low FS vs unburnt	***	***	***	***	***	***	***	***
Mod FS vs unburnt	***	***	***	***	***	***	***	***
High FS vs unburnt	***	***	***	***	***	***	***	***
Very high FS vs unburnt	***	***	***	***	***	***	***	***
log(Total rainfall)	**	***	**	**	***	***	**	**
Aspect relative to NW	*	**	*	*	**	*	.	
log(Bioturbation cover)	*	*	*	*	*	*	*	
log(Slope length FP)	*	*	.	*	*	*	NS	.
Slope degree	NS	NS	NS	NS			NS	*
Planar vs concave	*	*	*	*	*	*		
Convex vs concave	NS	NS	NS	NS	NS	NS		
Lower vs drainage		*		*				
Mid vs drainage		.		.				
Ridge vs drainage		.		.				
Upper vs drainage		NS		NS				
Canopy cover			NS	NS		NS	.	
AIC	452.8	453.2	453.5	453.8	454	454.1	454.7	469
ΔAIC	0	0.44	0.75	1.06	1.22	1.34	1.91	16.23
No of model parameters	11	15	12	16	10	11	10	7
Number of variables	7	8	8	9	6	7	6	4
Area under the curve	0.8766	0.8766	0.8764	0.8797	0.8718	0.8751	0.8701	0.8568
R-sq. (adj)	0.39	0.39	0.39	0.39	0.39	0.39	0.38	0.35
% explained deviance	37.3	37.3	36.4	37.6	35.4	35.8	34.6	32

Models 1-7 are the seven best models. The alternative management model (Alt) is based on the variables described in the environmental assessments (Table 1). Fire size is based on the slope length predictor variable.

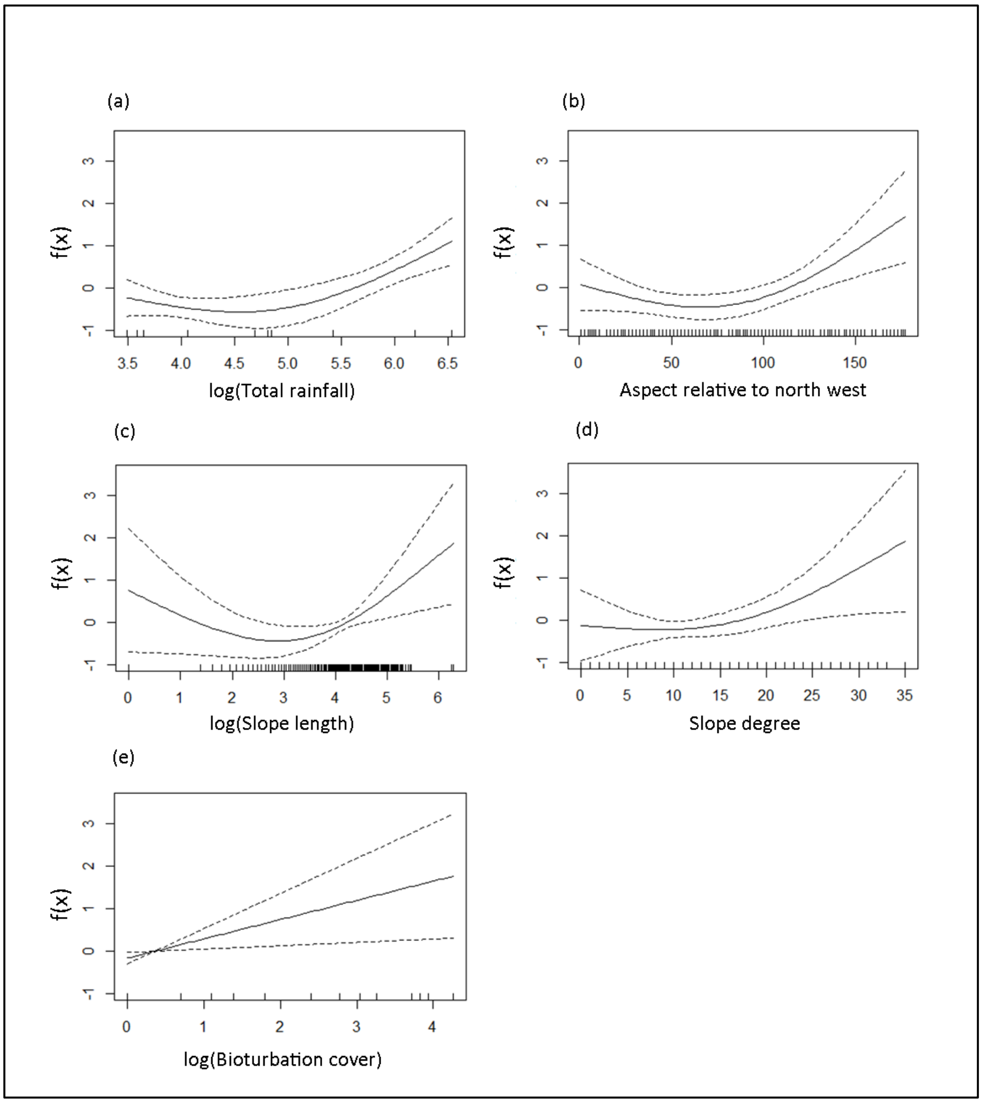

Fig. 5. Spline functions from the best model (model 1) of the probability of sediment movement occurring. Plots are the smoothed effects of each predictor after removing the effect of the other predictors in the model. These plots represent the shape of the relationship between the predictor (x-axis) and the probability of sediment movement occurring (y-axis). All of the plots are on identical scales for the y-axis to allow comparisons between variables; that is, steeper lines represent greater rates of change per unit of the predictor. Marks on the x-axis represent the location of data points in order to demonstrate the distribution of data. Dotted lines are 95% confidence intervals.

a) total rainfall, b) aspect relative to NW, c) fire perimeter slope length, d) slope degree, e) bioturbation

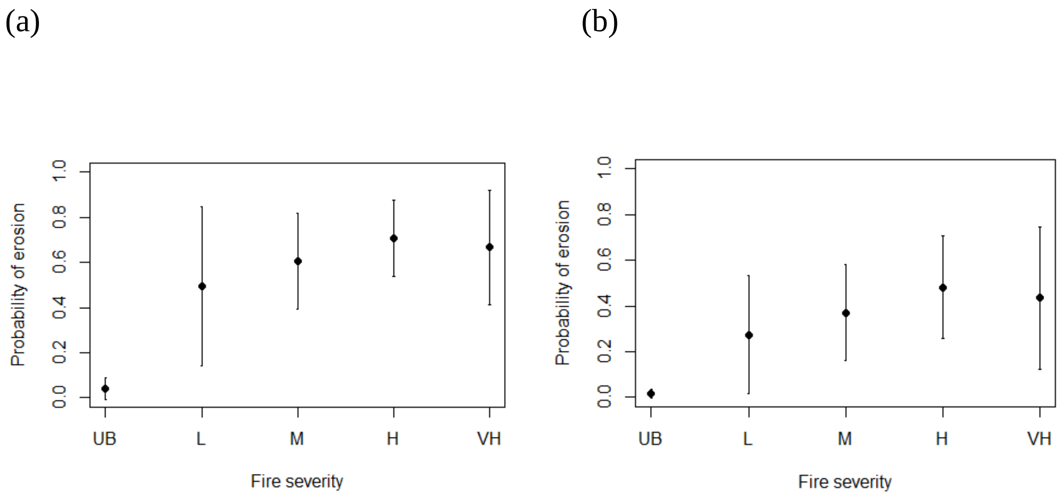

Fig. 6. Probability of sediment movement occurring as a function of fire severity in response to rainfall quartiles, a) upper quartile total rainfall (490 mm) and b) lower quartile total rainfall (38 mm). Prediction includes the variables of mean slope length (45 m), 18 degree angle, NW aspect, mean bioturbation cover (1.4%) and planar cross-slope curvature.

Class 3 sediment movements were not recorded in unburnt or low severity sites (Fig. 7). When the fire severities were high or very high, sediment movement in Class 1 was most likely (Fig. 7). By contrast, when fire severities were between moderate or lower, sediment movement was minimal (i.e. mainly Class 0 and some Class 1, Fig. 7). Of the 342 sites within the burn perimeters 22 sites were considered unburnt. Unburnt sites created patchy fire severity mosaics within the prescribed burns (Fig. 8). At Wotton, Belair S09, Warren and Kangaroo patchy unburnt sites were recorded. Sediment movement at all patchy severity sites (except for two at Kangaroo) were classed as 0.

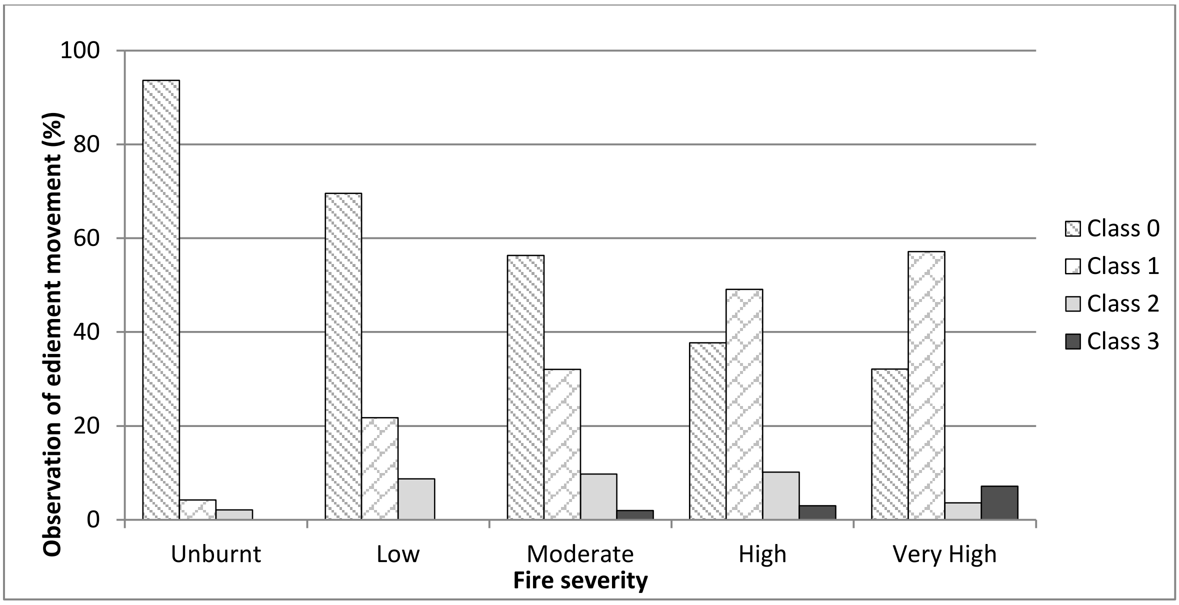

Fig. 7. Comparison of sediment movement observations within each fire severity classification. Sediment movement classes are expressed as a percentage of the total number of observations for each fire severity class.

N =505 (Unburnt n=84; Low n=23; Moderate n=10; High n=67; Very high n=28)

Fig. 8. Kangaroo Gully prescribed burn with patchy areas of unburnt vegetation and incomplete combustion of litter on the soil surface.

Within the preferred set of models the topographic properties including, aspect, slope length, slope degree, hillslope position and cross-slope curvature all contributed to the prediction of sediment movement occurring. South-eastern aspects increased the probability of sediment movement occurring (Fig. 5b). Aspect was included in all of the best set of probability models as either a significant relationship (P <0.05, six of seven models) or a marginal effect (P <0.1, one of seven models) (Table 6, Fig. 5b). Slope length (Fig. 5c) was included in all of the best set of probability models as either a significant effect (P <0.05, five of seven models), marginal effect (P <0.1, one of seven models) or a non-significant relationship (P =0.15, one of seven models) (Table 7). Above 50 m the effect of slope increases in a linear manner (Fig 5c).

Slope steepness within the ten prescribed burns varied from 0 to 35 degrees (Fig. 5d). Slope degree was included in five of the best set of seven probability models as a non-significant relationship (P >0.13) (Table 7). Surprisingly, slope is not a significant predictor in any of the best models. Above 18 degrees the effect of slope increases in a linear manner (Fig. 5d).

In two of the best fitting models slope position was included. Lower slopes were significant (P <0.05) in relation to drainage lines for two of the seven models. The presence of sediment movement was less likely on lower slopes compared to drainage lines. Upper slopes were not significant (P >0.1) in relation to drainage lines for two of the seven models. Both mid-slope and ridge positions contributed a marginal effect (P <0.1) in relation to drainage lines for two of the seven models. Planar cross-slope curvatures were significant in relation to concave in six of the seven models (P <0.05) whereas convex slopes were not significant (P >0.1) compared to concave slopes in all models. Concave cross-slope curvatures were more likely to experience sediment movement compared to planar cross-slope curvatures.

Bioturbation cover had a significant effect (*P* <0.05) in all best fitting models (Table 6). Increased bioturbation cover increased the probability of sediment movement occurring (Fig. 5e); however the 95% confidence intervals also increased as the cover increased. Bioturbation was visible on 129 of the 505 sites. The types of bioturbation observed included diggings, scratchings, burrows, tracks, mounds, holes and worm castings. When bioturbation was present the average surface cover was 6.5%; if diggings and scratchings were involved the average surface cover was 13.0%. The mean cover of bioturbation at all sites was 1.7%.

An alternative regression model incorporating the four variables used in the existing pre-burn environmental assessments (Table 7) had a good fit with an AUC of 0.86 and explained 32.0% of the model deviance. The AIC point rose by 16.23 when only the management variables were considered, suggesting no support (Burnham and Anderson 2001) (Table 7).

Discussion

Prescribed burn erosion assessment

The presence of erosion after prescribed burning in the study area was extensive in area but small in magnitude. Sediment movement was minor as evident by the clear lack of major erosion features such as erosion gullies, debris flows or numerous rills. The main types of features observed were splash pedestals and small wash deposits indicating only localised sediment movement (Fig 2, 3).

Our results support other studies (Benavides-Solorio and MacDonald 2005; Coelho *et al.* 2004) that reported minimal erosion following prescribed fire. These results are not consistent with those reported by Moffet *et al.* (2007) or the debris flow case study provided by Cawson *et al.* (2012). Moffet *et al.* (2007) found that rill erosion was the dominant erosion process following fire and that soil erosion increased 100 times following prescribed fire. Our different result may be attributed to the other studies having higher fire severities, less spatial coverage in their experimental designs, larger fire sizes and the use of simulated rainfall rather than observing natural rainfall conditions.

The types of movement observed in the study area such as splash pedestals were likely to contribute to the redistribution of nutrients and seeds within the soil profile but were unlikely to be responsible for substantial removal of the surface soils. Although this study did not observe any high magnitude events such as the debris flow described by Cawson *et al.* (2012), the potential for high magnitude events in the Mount Lofty Ranges is possible. Landslides and bog failures have been reported in the local area (Buckman *et al.* 2009; Middelmann 2007); however at this stage none has been reported in relation to prescribed burning.

Determinants of erosion

Based on the preferred model (Table 7) the main variables that could be used for pre-burn environmental assessment include fire severity, rainfall, aspect relative to north-west, bioturbation, slope length and slope degree. In the study area the presence of Class 3 sediment movement only occurred where the fire severities were moderate or higher (Fig. 7). A switch in fire severity from high to low reduced the likelihood of sediment movement occurring by 0.2 (Fig. 7). These results are in contrast to the outcomes of Cawson *et al*. (2011) who found on planar slopes little difference in sediment yields between high and low fire severities. Our results support the finding by Benavides-Solorio and MacDonald (2005) and Dragovich and Morris (2002b) that fire severity is one of the most important factors controlling post-fire erosion rates.

Fire severities varied from low to high within the ten prescribed burns. Six percent of the burnt dataset was comprised of unburnt patches (Fig. 8). In relation to unburnt patches reducing sediment loads – our results supported the finding by Cawson *et al.* (2011) that unburnt patches on a burnt hillslope are highly effective at reducing runoff and sediment from burnt areas above. There were no recorded unburnt patches within the Gate 17 burn where over two-thirds of the burn showed evidence of sediment movement and in some areas the sediment left the burn perimeter. All patchy severity sites apart from two at the Kangaroo burn were classed as 0, indicating no evidence of sediment movement occurring. Prescribed burns that are patchy (i.e. with unburnt areas) may result in minimal erosion potential.

Rainfall is considered a major cause of post-fire erosion (Inbar *et al.* 1998; Moody and Martin 2001b; Prosser and Williams 1998; Shakesby and Doerr 2006). Class 3 sediment movement only occurred at sites with a total rainfall over 108 mm. The prescribed burn with the most sediment movement experienced a 1 in 5 year rainfall event. Daily rainfall needed to be 20 mm or more for records of Class 3 sediment movement to occur. As rainfall increased, the trend for sediment movement to occur also increased (Fig 5a). Although the probability model in this study used total rainfall, a more reliable measure may be the intensity of rainfall. Based on research by Inbar *et al.* (1998) and Moody and Martin (2001a) we consider that differing rainfall intensities could alter the potential magnitude of erosion. Probability modelling of differing magnitudes of soil erosion following prescribed burning from differing rainfall intensities is required to test this hypothesis.

Aspects relative to north-west were also incorporated into the supported set of seven models as either a significant ($P < 0.05$) or marginal effect ($P < 0.1$) (Table 7). The presence of sediment movement tended to increase away from north-west aspects. This may be due to the indirect influence of wind. During winter, westerly winds bring moisture to the Mount Lofty Ranges and in summer northerly winds originating from Central Australia bring dry conditions (DEH 2009). These moisture gradients may have influenced the associated vegetation regrowth that subsequently provided stability to the recently exposed surface soils. Inbar *et al*. (1998) recorded a larger amount of sediment yield for southerly aspects in Israel during the first year post-fire, then little difference in subsequent years. In California, United States, Kinoshita and Hogue (2011) found that vegetation on the north and east aspect recovered quicker than south and west aspects due to retained soil moisture.

Topography influences soil erosion by varying a site's slope characteristics and drainage connectivity. Slope length was included in all of the supported set of models (Table 7) and slope degree was included in five of the supported set of models as a non-significant relationship (Table 7). Areas with short slope lengths reduce the runoff potential (Kirkby *et al.* 2005) which in turn reduces the likelihood of runoff velocities capable of entraining and transporting sediment. To generate Class 3 sediment movement the minimal slope length recorded at Mount Lofty was 40 m. Sediment movements were less likely on planar compared to concave cross-slope curvatures. These results support those of Benavides-Solorio and MacDonald (2005) who found that swales generally produced more sediment per unit area than planar hillslopes. Terrestrial laser scanned models from the Southern Mount Lofty (Morris *et al.* 2012) also highlighted that larger amounts of sediment movement occurred on concave cross-slope curvatures. It is interesting to note that the 18 degree slope threshold, above which we observe an increased probability in sediment movement, is also the geotechnical engineering threshold used in the prescribed burning review of the environmental assessments (Table 1).

Bioturbation was a significant (*P* <0.05) predictor variable in all of the supported seven models (Table 7). The influence of bioturbation on post-fire erosion depends on the location and associated fauna. At the study area the degree to which bioturbation influenced the sites depended on the presence of burrowing or digging fauna species. Mound-building ants and surface-digging lyrebirds observed in the Blue Mountains (Dragovich and Morris 2002a; Richards *et al.* 2011) were either limited (ants) or non-existent (lyrebirds) in the study area. The types of species moving surface material in the study area were bandicoots, echidnas, worms and limited mound-building ant species.

Implications for environmental assessment of burning operations

Environmental assessment in relation to erosion from prescribed burning relies on predicting the occurrence and magnitude of sediment movement. Nine out of ten pre-burn environmental reviews focused on the slope steepness of over 18 degrees (Table 1). The threshold value of 18 degrees is derived from a 1:3 slope gradient (1:3 gradient equals 18.43 degrees). In this study the probability of sediment movement occurring increased from 18 degrees onwards (Fig. 6). Gyasi-Agyei (2006) considered that prescribed burning on slopes steeper than 20 degrees may not be appropriate emphasising the need for reliable data.

Based on our results, sediment movement after burning on slopes steeper than 20 degrees depends on all the variables identified in our modelling. For example, based on the best model (Table 7) the probability of sediment movement occurring on 20 degree slope can vary from 0.20 to 0.63 for low fire severity and 0.38 to 0.81 for high severity fire, when the numerical predictor variables are altered from the lower to the upper quartile. To reject burning based solely on the slope angle is not supported by our probability model. Given the need to incorporate more environmental variables there is a clear need to develop more robust post-fire erosion models for South Australia such as those described by Robichaud and Ashmun (2012) to assist land managers working in the post-fire environment.

Further research is needed in order to predict sediment movement within differing landscapes containing varied vegetation types and climates. The magnitude of post-fire erosion is also a significant management issue (Cawson *et al.* 2012). Whilst this study modelled the probability of sediment movement occurring, the limited data on high magnitude events such as Class 3 and above precluded the reliable modelling of differing magnitudes. Given the limited data available on high magnitude events there is a clear need to collect more information of this kind.

Conclusion

Following the ten prescribed burns in the Southern Mount Lofty Ranges sediment movement was minimal as evident in the types of erosion features observed such as splash pedestals. Unburnt patches within the ten prescribed burns reduced the erosion potential. Evidence of sediment washes leaving the burn perimeters was negligible in six of the burns and minor in the other four.

Based on generalized additive modelling this study concluded that a suite of environmental variables is more reliable to determine the occurrence of sediment movement than focusing only on slope steepness. Fire severity was a highly significant environmental determinant for the presence of sediment movement after prescribed burning. The main determinants of sediment movement derived from the best set of models included nine variables: fire severity, rainfall, slope degree, slope length, aspect, bioturbation cover, canopy cover, cross-slope curvature, and hillslope position.

Management implications from this study relate to environmental assessments, operational burning and future research. Environmental assessments need to consider a range of environmental influences rather than relying on slope steepness. Burning operations need to appreciate the significant influence that fire severity has on sediment movement. There is also a clear need to incorporate spatial sampling designs into both erosion assessments and future post-fire erosion studies.

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Chapter 4: Sediment trapping after a wildfire at Mount Bold

Hay bale sediment barrier near the reservoir four months after the Mount Bold wildfire

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4.2 Statement of contribution

As primary author I was responsible for the conceptualisation of the work by collaborating with SA Water on the need to research post-fire mitigation efforts. I was involved in the realisation by inspecting the sediment trap installation, field inspections of the trap success, data analysis and the primary preparation of the manuscript. Staff of SA Water, including S Calliss, J Frizenschaf and M Blason were involved in the conceptualisation and realisation of the sediment trapping program after the Mount Bold Wildfire, a subcomponent of the monitoring effort and minor edits of the manuscript. The role of S Calliss included the conceptualisation of the types of sediment traps installed, assistance in determining appropriate installation locations, data collection, soil and water quality sample collection, evaluation of the trapping success and minor drafting of the manuscript. The role of D Dragovich, M Henderson and B Ostendorf was advice on the research conceptualisation and editing of the manuscript. I presented the paper at the 'Water Down Under 2008' conference incorporating 31st Hydrology and Water Resources Symposium and the 4th International Conference on Water Resources and Environment Research in Adelaide, Australia. Two anonymous reviewers provided comments on the paper.

I hereby certify that the statement of contribution is correct.

R Morris (Candidate) 23/1/13 Date

I hereby certify that the statement of contribution is correct and I give permission for the inclusion of the paper in the thesis.

S Calliss 4/2/2013 Date

J Frizenschaf 24/1/2013 Date

M Blason 24/1/13 Date

M Henderson 24 JAN 2013 Date

D Dragovich 31-1-13 Date

B Ostendorf 23-1-13 Date

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International Association of Hydrological Science, IAHS Press, Centre for Ecology and Hydrology, Wallingford, Oxfordshire OX10 8BB, United Kingdom.

5.2 Statement of contribution

As primary author I was responsible for the conceptualisation of the work by combining the use of sediment traps, erosion pins and terrestrial laser scanning to study post-fire erosion. I collaborated with SA Water on the sediment trapping and I collaborated with Maptek Pty Ltd to implement the terrestrial laser scanning. I was involved in the realisation by monitoring the sediment traps, installing and measuring the erosion pins and conducting the terrestrial laser scanning with the help of James Moncrieff. I analysed the data and prepared the manuscript. The role of D Dragovich and B Ostendorf was advice on the research conceptualisation and editing of the manuscript. I presented the paper at the International Committee on Continental Erosion (ICCE) of the International Association for Hydrological Science (IAHS) international conference 'Wildfire and water quality: processes, impacts and challenges' Banff, Canada, 11–14 June 2012. Two anonymous reviewers provided comments on the paper.

I hereby certify that the statement of contribution is correct.

____________________________R Morris (Candidate) 23/1/13 Date

I hereby certify that the statement of contribution is correct and I give permission for the inclusion of the paper in the thesis.

D Dragovich 31-1-13 Date

B Ostendorf 23-1-13 Date

Morris, R., Dragovich, D. & Ostendorf, B. (2012) Hillslope erosion and post-fire sediment trapping at Mount Bold, South Australia.
Wildfire and water quality: processes, impacts and challenges, 11-14 June, Publication 354, pp. 42-50

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Chapter 6: Discussion and Conclusion

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Prescribed burn at Greenhill in the Southern Mount Lofty Ranges
(Courtesy: Pip McGowan, Country Fire Service Promotion Unit)

6.1 Overall significance and contribution to knowledge

Evidence-based management of sediment movement from both prescribed fire and wildfire can reduce potential erosion and hence protect regional natural services such as soil profile formation, soil mineral health, regulating water quality and maintaining local landscape character. Managing post-fire erosion requires an appreciation of the natural processes, an understanding of the erosion risk and a working knowledge about the success of implementing potential mitigation or remediation strategies. Post-fire soil erosion is a natural process that can be influenced by differing fire management practices.

This thesis has the overarching goal of developing evidence-based options for managing post-fire sediment movement in the Southern Mount Lofty Ranges. This goal was achieved by evaluating various methods of assessing post-fire erosion, identifying the environmental determinants that influenced sediment movement from prescribed burning; determining if management intervention could prevent sediment movement post-wildfire; and assessing hillslope erosion in relation to post-wildfire sediment trapping at the water reservoir at Mount Bold, South Australia.

In this thesis suitable methods for assessing post-fire erosion were compared and identified. It was concluded that monitoring of post-fire erosion requires an appreciation of the spatial variability of the topography (Ch 2, 3, 5; Aim 1). The simple framework developed in this research to implement rapid onsite assessment of post-fire erosion may enhance the land manager's ability to monitor after burning (Ch 2, 3; Aim 1- 2). This framework is being incorporated into post-prescribed burning field assessments for South Australian managed reserves (*pers. comm*. Mike Wouters 2012). The trialling of novel erosion measurement methods in Chapter 2 such as terrestrial laser scanning and digital close range photogrammetry has highlighted their potential to increase the vertical accuracy and spatial coverage of future post-fire erosion studies (Ch 2, Appendix D2; Aim 1). The high variability of sediment movement needs to be considered in order to accurately predict the risk of erosion following fire and to monitor erosion responses after fire. Detailed point measurements are not representative of the hillslope or catchment wide responses. Point measurements need complementary evidence derived from new spatial technologies and cost efficient rapid visual assessment techniques in order to accurately assess the regional risk and impact of fire.

Chapter 3 addressed the probability of erosion occurring after prescribed fire in relation to a suite of predictor variables including fire severity, rainfall, aspect, bioturbation, slope length, slope angle and cross-slope curvature. The regression model developed in this study may improve the prediction of erosion following prescribed fire (Ch 3; Aim 2). It was concluded that fire severity was the most significant variable in determining whether sediment movement occurred after prescribed burning (Ch 3; Aim 2) and, in the study area, altering the fire severity from high to low during prescribed burning will decrease the probability of sediment movement (Ch 3; Aim 2). Research findings supported the propositions that patchy fire severities will reduce potential sediment movement (Ch 3; Aim 2) and that sediment movement is often localised, most likely staying contained within the hillslope after prescribed burning (Ch 3; Aim 2). Results from Chapter 3 indicate that more reliable predictions about the occurrence of sediment movement would result from considering a suite of environmental determinants, rather than following the previous local practice of focusing on slope steepness. Environmental assessments and research projects need to incorporate spatial sampling designs that appreciate the range of environmental determinants within the burn area.

A case study of erosion following a wildfire at Mount Bold (Chapters 4 and 5) was used to understand the patterns of post-fire sediment movement and the success of implementing sediment traps to minimise the impact of sediment movement on water quality. Research findings concluded that sediment barriers will reduce but not prevent post-fire charcoal-rich sediment and debris reaching water reservoirs after a 1 in 5 year rainfall event (Ch 4, 5; Aim 3, 4). Installation of sediment barriers after wildfire may fail due to excessive sediment movement attributed to steep slopes (35-45 degrees), high water velocity and minimal vegetation cover (Ch 4, Aim 3). Results based on erosion pins, sediment barriers and terrestrial laser scanning suggested that patterns of sediment movement are influenced by hillslope morphology including cross-slope curvature, steepness, position and length (Ch 3, 5; Aim 2, 4). Successful placement of sediment barriers would benefit from a working knowledge about erosional links to hillslope morphology (Ch 5; Aim 4).

6.1.1 Soil profile formation and soil mineral health

Post-fire soil erosion can alter the natural environment by altering soil profile formation and soil mineral health. After both wildfire and prescribed fire in the study area soil surfaces may be eroded (Ch 3, 4, 5), leaving the shallow rocky soils on the upper slopes devoid of nutrient-rich material and the foothill slope positions buried in nutrient-rich sediment. Within the hillslope, micro-topographical features such as litter dams and micro-terraces trap sediment causing localised variation in the soil profile (Ch 2, 3). Observation of litter dams and terraces in the study area support the findings of Mitchell and Humphreys (1987) that litter dams and terraces may contribute to texture contrasts in soil profile formation. Litter dams trap soil minerals and viable seeds resulting in concentrated areas of plant growth. Entrained sediment trapped by plant growth contributes to soil profile development via litter dam formation. Furthermore alteration of the soil profile may affect the multitude of organisms that spend part of their lives underground contributing to the soil-based ecological processes.

Fire can alter soil profile formation and soil mineral health by altering rates of sediment movement. The occurrence of sediment movement is influenced by a suite of variables including fire severity, rainfall, aspect, bioturbation, slope length, slope angle and cross-slope curvature (Ch 3, 4, 5). Predicting the occurrence of sediment movement requires an understanding of the variables that may influence the magnitude of erosion. Patchy fire severities in the study area (Ch 3) reduced the occurrence of sediment movement by trapping and retaining moving sediment in unburnt or low severity burnt areas. These findings support research by Cawson *et al.* (2011) who also described patchy severities reducing sediment yield. Low severity prescribed burning will protect soil profiles by minimising the occurrence of sediment movement (Ch 3).

Soil profile formation can be influenced by altering spatial patterns of both prescribed fire and wildfires. The influence of hillslope morphology was highlighted in Ch 3 and 5. Concave cross-slope curvatures and long slope lengths increase the probability of sediment movement. These findings are consistent with those of Benavides-Solorio and MacDonald (2005) who found that planar topographical positions were less likely to yield sediment than swales. In areas where soil formation is a concern, strip burns can be implemented to reduce overall slope length for sediment transfer. In the case of major wildfires, retaining the vegetation immediately adjoining the water's edge will create buffer zones that may trap any mobilised sediment. Preventing the entire catchment from burning diminishes the influence of hillslope morphology and the associated hydrological influence of drainage connectivity on erosion.

6.1.2 Water Quality

Post-fire sediment delivery into water channels can result in alterations to the existing water quality. Smith *et al*. (2011) found that the range of wildfire impacts on water supplies across south-eastern Australia included increased fluxes of sediment, nutrients and other water quality parameters that may potentially contaminate water supplies. In the case of the 2007 Mount Bold wildfire (Ch 4,5, Appendix B) the antecedent water conditions and retention of sediment within the hillslope possibly prevented the detrimental water quality impacts recorded in other locations as described by Smith *et al*. (2011).

Options to actively manage potential negative fire-effects on water quality include fire avoidance, prescribed burning to reduce the risk, installing sediment barriers to capture sediment flux, construction of adequate water filtration treatments to cope with increased sediment loads and contaminants or the drawing of water from alternative sources. This thesis has explored the options of prescribed burning and sediment barriers (Ch 3, 4). The choice of water filtration plants and alternative water sources forms part of the future directions for this work (see section 6.3).

Prescribed burning in the study area is used to reduce the risk of wildfires. In water reservoir reserves the use of prescribed burning has been reintroduced in the Mt Lofty Ranges since 2008. The use of low to moderate severity prescribed burning in the water reservoirs will generally result in minimal sediment movement (Ch 3). Most of the sediment will be retained within the hillslope due to litter dams, micro-terraces, unburnt patches and other localised sinks created by micro-topographical traps. The regression model developed in Chapter 3 will assist in predicting the potential occurrence of sediment movement from prescribed burning. Fire managers in the study area can also minimise erosion by altering the spatial coverage of the burn to reduce potential water connectivity by using strip burns to minimise slope lengths and burning in spring to reduce the likelihood of rainfall immediately following the fire event.

In order to reduce post-fire water quality problems, fire managers have installed sediment barriers to reduce sediment delivery to water reservoirs (Cerda and Robichaud 2009). In the case of Mount Bold (Ch 5) sediment barriers will reduce but not prevent post-fire charcoal-rich sediment and debris reaching water reservoirs after a 1 in 5 year rainfall event. Although water quality at Mount Bold was not adversely affected by the wildfire in 2007 (Ch 4, Appendix B, Morris *et al*. 2009), the long term impact for potential contamination from accumulated post-fire sediment is not known.

The sediment traps at Mount Bold did not capture all sediment (Ch 4 and 5) but they may have prevented a large initial flush of sediment following the first major rainfall event. Emelko *et al.* (2011) discussed the complexity of treating variable post-fire water quality and how a ‘rapid recovery’ during water treatment may require parameters such as turbidity to reach normal baseline values within hours, days, or weeks depending on the available water storage capacity. If a ‘rapid recovery’ was not possible then a robust design and operation of water treatment processes is particularly critical. In the case of Mount Bold the water treatment plant was sufficient for high turbidity levels and was not affected by the first flush (Ch 4, 5, Appendix B). In other Australian water catchments the water treatment plant may not be as robust. This situation was evident in the Cotter catchment in Canberra where a new major water filtration plant was built to address the turbidity and other water quality problems that arose after the 2003 wildfires (White *et al.* 2006).

6.1.3 General landscape character

Post-fire sediment movement influences landscape character by removing surface soils, redistributing soil nutrients, forming features like rills, gullies, pyro-colluvial fans and debris flows, depositing nutrient rich sediment along the lower portion of hillslopes and altering drainage systems (Ch 2-5, Appendices). The spatial scale of these alterations varies from the asymmetrical formation of hillslopes (Wilkinson and Humphreys 2006) to the micro-features of litter dams and microterraces (Mitchell and Humphreys 1987). The general landscape character of the study area could be altered depending on fire management practices and prevailing climatic conditions. Prescribed burning in the Mount Lofty Ranges tended to create minimal sediment movement (Ch 2) whereas the Mount Bold wildfire created substantial sediment movement (Ch 4-5).

The most dramatic alterations to general landscape character are caused by major wildfires where severe fire intensities over large areas result in entire catchments being burnt (Ch 4-5). Protective vegetation is altered and exposed soils are subject to severe erosion problems (Ch 1 and 4). In these cases rills, debris flows, pyro-colluvial fans and gully erosion alter hillslope morphology. Although major wildfires are not a regular event in the Southern Mount Lofty Ranges they have historically altered the geomorphology of the area as evidenced by the sediment records detailed at Wilson Bog (Appendix A). Patterns of sediment distribution range from small features such as splash pedestals, litter dams and micro-terraces through to large areas influenced by major debris flows and mass deposition (Ch 2, Appendix A). These different deposition patterns create micro- and macro-habitats with differing soil nutrients and depths within the soil profile. The differing morphological units created by post-fire sediment movement influence the type of vegetation growth, associated fauna and general landscape character. This thesis supports the findings of Moody and Martin (2009) that wildfires are an important geomorphic agent of landscape change.

6.2 Problems encountered

The extent to which conclusions in this thesis can be generalised are limited in scope due to the difficulties in accurately measuring post-fire erosion and the localised experimental setting in the Southern Mount Lofty Ranges. Problems in relation to measuring erosion have been highlighted by numerous authors (Croke and Hairsine 2006; Stroosnijder 2005). Problems specific to this thesis have been grouped into four main categories: 1) spatial scale, ii) temporal scale, iv) equipment, and iv) experimental setting.

Interpretation of erosion data is limited by the issue of spatial scale. Post-fire erosion studies using point or plot scale data tend to report higher soil redistribution rates than studies that focus on hillslope or catchment scales (Shakesby and Doerr 2006). The extrapolation of data from smaller areas to larger areas is limited as the erosion processes and ecohydrological connectivity differs depending on the spatial scale at which the study is conducted (Allen 2007). To exacerbate this issue the experimental location can also alter the erosion data outcomes as the occurrence of sediment movement differs depending on where in the topography the experiment is conducted (Ch 3, 5; Benavides-Solorio and MacDonald 2005). Water quality conclusions from Mount Bold were limited in spatial representation, replication and temporal periods due to the pre-determined water sampling strategy conducted by SA Water. The spatial design of any post-fire erosion studies will influence the data quality and potentially limit the conclusions that can be drawn.

In order to obtain greater spatial coverage within the landscape this thesis focused on sediment movement rather than the usual approach where both runoff and sediment delivery are measured. Focusing on sediment movement enabled the collection of a larger number of sample points across more diverse topographic positions than previous post-fire erosion/runoff studies. This different approach enabled the application of alternative statistics to those usually applied to erosion plot data. The limitation of not using erosion plots is that reliable runoff measurements were not made, limiting the overall appreciation of erosion processes occurring in the study area and the potential for the thesis data to be reliably used in future hydrological models.

Temporal scales are also a limiting factor in post-fire erosion studies. Wildfires are unpredictable in nature thereby limiting the feasibility of pre-fire data collection. Occasionally opportunistic studies may use existing pre-fire data, but usually the researcher is limited to finding a surrogate reference site that may indicate both pre-fire and unburnt conditions. Installation of post-fire erosion measuring equipment is ideally undertaken prior to the first rainfall event. This is not always possible, as experienced with the erosion pins installed at Mount Bold (Ch 5). Prescribed fire can be used to remove the unpredictable nature of wildfires. However the fire severity is often much less than for wildfires and as such the post-fire erosion impact generally differs substantially (Ch 2-5).

Few long term studies have been published regarding post-fire erosion. In short-term post-fire erosion studies vegetation regrowth is reported as being substantial in the first six months then continues to provide further ground cover in subsequent years. As the most dramatic effect is measured in the first year most studies do not continue in the subsequent years. Data has been collected for three years following the Mount Bold wildfire but at this stage the information is awaiting further analysis and data collection which is beyond the usual timeframe for completion of postgraduate studies.

To sufficiently address the issue of fire frequency and erosion both long term measurement studies (eg Cerda and Lasanta 2005; Moody and Martin 2001) and sedimentary records of palaeofires (Appendix A) need more research attention. The use of palaeofire sedimentary records do not presently give true indications of fire records as differing fire severities and rainfall intensities alter the likelihood of post-fire deposition. Many palaeofire studies are located away from the sediment source resulting in the recording of mixed post-fire depositional events. Wilson Bog (Appendix A) was unique in that it was located in close proximity to the water divide. However, only limited general conclusions can be made due to Wilson Bog being only one site within the study area. The possibility of including additional palaeofire stratigraphic sedimentary records is included in Section 6.3 (future directions of the work).

This thesis used a variety of differing erosion equipment techniques to overcome limitations in measuring post-fire erosion. Chapter 2 discusses the differing methods in greater detail. A novel approach of using a terrestrial laser scanner was employed to overcome many of the spatial scale issues by measuring the entire hillslope surface. TLS limitations in 2007 included a range accuracy of only 50 mm and a maximum range of 700 m, along with regrowth of vegetation inhibiting the penetration of laser technology. Newer TLS technology (Maptek 2012) has a range accuracy of 10 mm and a maximum range of 2000 m. Another novel approach used by this research was digital close range photogrammetry, which has great potential to provide detailed surface models of micro-topographical features. The use of new techniques is discussed further in section 6.3. Another erosion assessment technique not pursued in this thesis was the use of tracers due to logistical and monetary constraints.

The final grouping of problems focuses on experimental setting. This thesis was specific to the Southern Mount Lofty Ranges and as such the experimental setting is limited to this study area. General conclusion are applicable to the study area, however extrapolation to areas beyond the experimental setting are limited by the unique environmental attributes of the study area including the latitudinal position, climate, geology, vegetation, faunal species and local fire management practices.

This thesis also focused on natural environmental conditions rather than experimental settings where either the fire severity was altered through controlled burning or rainfall intensity was generated using rainfall simulators. Advantages of field research under natural conditions include being able to conduct measurements at the actual scale with genuine soil and plant characteristics. In contrast laboratory or rainfall simulated experiments allow better control of the range of dependent variables and the ability to replicate measurements.

6.3 Future direction of the work

Managing post-fire erosion warrants further research due to the potential impacts that may occur to natural services, the risks involved in potential damage to infrastructure and the threats to human health. The following research ideas warrant further investigation beyond the work provided in this thesis.

Environmental assessment of erosion from prescribed burning requires a sound understanding of the environmental determinants, associated processes and spatial arrangements. Future research could expand the regression modelling applied in Chapter 3 by obtaining high magnitude soil erosion data. Features that were missing in the study area prescribed burn data included landslides, gully erosion, pyro-colluvial deposits and debris flows. Additional data would enable the identification of the key threshold levels of environmental determinants where erosion consequences are likely to impact on water quality and human infrastructure. Regression modelling could be incorporated into a geographical information system (GIS) to analyse the optimal spatial configuration of burning. It is still questionable which burn design would minimise the potential impacts of erosion on water reservoirs. Differing spatial burn patterns need assessment to determine the optimal configuration to reduce the fire risk with regard to minimal erosion. Different burn patterns that need assessing include: i) the entire catchment, ii) sub-catchments, iii) hillslope strip burns, or iv) strategic ridge-tops. Research is also needed into the success of reducing erosion by creating unburnt drainage buffers and mosaic unburnt patches.

The term 'leverage' has emerged as a ratio measurement into the effectiveness of prescribed burning at the landscape scale. Leverage is the ratio of reduction of average area of unplanned fire to average area treated (prescribed burnt) (Bradstock *et al.* 2012). There is potential to combine this thesis with the leverage concept to better understand how prescribed burning could be used to protect water quality. Previous research by Wohlgemuth *et al.* (1999) highlighted the potential for prescribed burning to reduce potential erosion from wildfires. By combining the outcomes of this thesis in relation to fire severity and erosion with emerging research by Price and Bradstock (2011) on the effectiveness of prescribed burning, there is potential to determine if prescribed burning may protect environmental attributes such as water quality.

Fire frequency is often identified as an area of research that is needed in relation to the long-term impact of post-fire erosion and ecological processes (eg Cawson *et al*. 2012; York *et al.* 2012) To address this issue both palaeofire and long-term recent fire studies are required. More study sites are needed similar to Wilson Bog (Appendix A) to determine long-term erosion records in relation to fire frequencies. In particular, this should involve charcoal bearing sediments deposited directly on site rather than from lake environments located far from the initial site of erosion. At Mount Bold the erosion pins have remained installed to enable longer term studies (eg over 10 years) to be reported. This information may aid in understanding landscape resilience in relation to erosion from differing fire frequencies.

Managing post-fire erosion in relation to water quality crosses numerous academic disciplines. There is merit is linking with water filtration engineers to better understand the impact of the first flush of sediment following fire and the potential impact it may have on local filtration systems. It may be that the timing of sediment pulses is more important than the overall amount of sediment movement after a fire as indicated by Emelko *et al.* (2011). If managing the first flush is of paramount importance then managers need to derive an alternative water source and/or implement a program similar to the recently established Victorian Bushfire RRATs (bushfire rapid risk assessment teams), NSW/ACT BAAT (burnt area assessment team) (PCL and NPWS 2010), or the well-established United States Department of Agriculture Forest Service BAER (burned area emergency rehabilitation) (Robichaud and Ashmun 2012).

The construction of sediment barriers may be improved by working with civil engineers into the design of current sediment barriers. There is merit in trialling the feasibility of installing rock gabions in areas where hay bales previously failed. Areas of failure were most noticeable at the base of steep slopes and in concave topography where water drainage converges. In the western US the use of mulches is emerging as a successful treatment to reduce erosion post-fire (Bautista *et al*. 2009). Applying mulches instead of using sediment barriers is an area of study yet to be explored in *Eucalyptus* forested areas. The role of micro-topographical features in retaining sediment on hillslopes after fire could be better understood with the use of use of digital close range photogrammetry and terrestrial laser scanning. These depositional features may aid in improving the design of sediment barriers for mitigation of post-fire erosion.

An important future direction for post-fire erosion management in Australia is to assess the feasibility of applying the erosion assessment 'tools' described by Robichaud and Ashmun (2012) that were developed by the US Department of Agriculture, Forest Service, Rocky Mountain Research Station. Although they are not tailored to the Australian environment the concepts, delivery and programming could be modified to assist Australian land managers with post-wildfire assessment and treatment decisions. These 'tools' will assist in guiding what evidence-based data is still required to adequately address managing erosion in the post-fire landscape.

6.4 Evidence-based management of post-fire erosion in the study area

This thesis has compiled scientific evidence to assist the decision making process in relation to managing post-fire erosion in the Southern Mount Lofty Ranges. The main points of evidence are:

- there is a large body of existing scientific literature regarding post-fire erosion (Ch 1) ;
- assessing soil erosion in the field requires an appreciation of the spatial variability of topography (Ch 2; Morris *et al*. 2011);
- post-fire erosion can be classified using the rapid visual assessment framework developed as part of this thesis (Ch 2; Morris *et al*. 2011);
- prescribed burning will result in sediment movement (Ch 3);
- environmental assessments need to consider more than just slope steepness to adequately address erosion concerns from prescribed burning (Ch 3);
- a suite of environmental variables is needed to predict erosion potential (Ch 3);
- sediment barriers reduce mobilised sediment from reaching water reservoirs, however they are likely to fail after a 1 in 5 year rainfall event (Ch 4; Morris *et al*. 2008, Ch 5; Morris *et al.* 2012); and
- larger amounts of sediment movement in the study area occur in concave compared to planar or convex cross-slope curvatures (Ch 5, Morris *et al*. 2012).

6.5 Conclusion

Management of post-fire soil erosion in the Southern Mount Lofty Ranges needs to take into account its potential influence on regional natural services including soil profile formation, regulating water quality and maintaining local landscape character. Assessing and predicting the influence of soil erosion on natural services is a complex process where the scale and methods employed can yield differing results. It was found that detailed point estimates of soil erosion provide a very limited understanding of sediment movement. A simple visual framework provided an affordable approach to collate large datasets in relation to post-fire erosion.

Using prescribed fire to manage fuel loads in the Southern Mount Lofty Ranges will mainly cause minor sediment movement. The probability of movement may be predicted based on a suite of variables including fire severity, rainfall, aspect, bioturbation, slope length, slope angle and cross-slope curvature. Fire severity was the most significant variable in relation to whether sediment movement occurred after prescribed burning. As this variable can be managed by altering the timing and pattern of fire ignition there is potential to substantially reduce soil erosion risk. With the assistance of detailed topographic mapping the influence of slope morphology can be incorporated into any pre-fire assessments. These findings highlight the need for fire management prescriptions to have the capacity to control fire severity and for fire planning to consider the spatial arrangement of burning strategies.

Wildfires do not provide the opportunity to prescribe the conditions under which the fire will burn. For wildfires, such as at Mount Bold, the resulting fire severity and spatial boundaries are largely dictated by the weather. Prediction and monitoring of post-fire erosion requires an appreciation of the spatial variability within the topography. Patterns of sediment movement are influenced by hillslope morphology, especially in relation to concave topography where converging hillslopes influence the hydrology.

Understanding the localised patterns of erosion will assist in the decision process of whether and where to mitigate soil erosion. Field evidence from Mount Bold indicated that sediment barriers after wildfire may fail due to excessive sediment movement attributed to steep slopes (35-45 degrees), high water velocity and minimal vegetation cover. Installation of sediment barriers will reduce but not prevent post-fire charcoal-rich sediment and debris reaching water reservoirs after a 1 in 5 year rainfall event.

Managing soil erosion in the post-fire landscape requires an appreciation of the natural processes and potential available mitigation options. Evidence-based management enables localised attributes such as rainfall characteristics to be considered when determining suitable mitigation strategies. Progress towards better managing post-fire soil erosion requires additional predictive models for differing magnitudes of sediment movement, localised erosion expertise and an appreciation of the spatial variability within the landscape both locally and internationally.

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Appendices

Mount Bold reservoir four months after the 2007 wildfire

Appendix A: Holocene palaeofire

Pyro-colluvial fan formation two weeks after the 2007 Mount Bold wildfire. Mount Bold was studied as a modern analogue of palaeofire processes. Along the base of the hill in the image is approximately eight metres of hay bales.

Appendix A was published as:

Buckman S, Brownlie KC, Bourman RP, Murray-Wallace CV, **Morris RH**, Lachlan TJ, Roberts RG, Arnold LJ, Cann JH (2009) Holocene palaeofire records in a high-level, proximal valley-fill (Wilson Bog), Mount Lofty Ranges, South Australia. *Holocene* **19**, 1017-1029. doi: 10.1177/0959683609340998

A1 Copyright details

Copyright holder of the work:

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A2 Statement of contribution

As a co-author I was involved in the conceptualisation of the work by providing a modern analogue from Mount Bold from which comparisons were made with the Wilson Bog palaeofire records. I provided a comprehensive literature review and field knowledge on sediment movement processes after fire. I was involved in the realisation by assisting in the field collection of sediment at Wilson Bog and running a field trip to the Mount Bold 2007 wildfire site for S Buckman and KC Brownlie. I was involved in editing the manuscript. S Buckman was the primary author, who decided to investigate the charcoal fragments found at Wilson Bog during a field trip with RP Bourman. S Buckman coordinated and attended the field components, developed the charcoal extraction method, organised the dating and collaborated with all the co-authors. KC Brownlie worked on the research as part of her honours project, contributed her thesis literature review, was involved in the realisation by completing extensive laboratory work and discussed the outcomes in her honours thesis. RP Bourman initiated the first field trip, attended the OSL dating field trip and provided extensive comment on the draft manuscript. CV Murray-Wallace conducted the OSL and radiocarbon dating fieldtrips and provided extensive comments on the manuscript. TJ Lachlan, LJ Arnold and R Roberts contributed to the OSL dating components including the D_e estimation and dosimetry. JH Cann provided honours supervision for KC Brownlie and provided editorial comments on the manuscript. Anonymous review was provided on the paper.

I hereby certify that the statement of contribution is correct.

____________________R Morris (Candidate) 23/1/13 Date

I hereby certify that the statement of contribution is correct and I give permission for the inclusion of the paper in the thesis.

S Buckman	29/1/13	Date
KC Brownlie	7/2/13	Date
RP Bourman	26/1/13	Date
CV Murray-Wallace	29/1/2013	Date
TJ Lachlan	29/1/2013.	Date
RG Roberts	1/2/2013	Date
LJ Arnold	7/2/2013	Date
JH Cann	25/01/13	Date

Buckman, S., Brownlie, K.C., Bourman, R.P., Murray-Wallace, C.V., Morris, R.H., Lachlan, T.J., Roberts, R.G., Arnold, L.J. & Cann, J.H. (2009) Holocene palaeofire records in a high-level proximal valley-fill (Wilson Bog), Mount Lofty Ranges, South Australia.
The Holocene, v. 19(7), pp. 1017-1029

NOTE:
This publication is included on pages 151-163 in the print copy of the thesis held in the University of Adelaide Library.

It is also available online to authorised users at:

http://dx.doi.org/10.1177/0959683609340998

Appendix B: Emergency response

NOTE:
This figure/table/image has been removed
to comply with copyright regulations.
It is included in the print copy of the thesis
held by the University of Adelaide Library.

Helicopter water bombing at the Mount Bold 2007 wildfire
(Courtesy: Kangarilla Country Fire Service, CFS Promotion Unit)

Appendix B: Emergency response in water reservoirs

Appendix B was published as:

Morris R, Calliss S (2009) Does an emergency response protect our water reservoirs? AFAC 2009 Conference Meeting Expectations, 21-24 Sept 2009, Surfers Paradise, QLD, 595-600. (AFAC: Melbourne)

B1 Copyright details

Copyright holder of the work:

Bushfire Cooperative Research Centre, Level 5, 340 Albert Street, East Melbourne, Victoria, 3002, Australia

B2 Statement of contribution

As primary author I was responsible for the conceptualisation of the work by identifying the need to present the outcomes of the Mount Bold Wildfire research to the broader fire management community. With assistance from S Calliss I compiled the data in relation to sediment traps. I obtained the fire operations details from the Country Fire Service and obtained the water quality data using the in-house SA Water program 'Waterscope'. I analysed the data and prepared the manuscript. R Bradstock, D Dragovich and M Blason provided minor comments on the draft manuscript.

I hereby certify that the statement of contribution is correct.

________________________________R Morris (Candidate) 23/1/13 ____________Date

I hereby certify that the statement of contribution is correct and I give permission for the inclusion of the paper in the thesis.

S Calliss 4/02/2013 Date

Does an emergency response protect our water reservoirs?

R.Morris[1,2] and S. Calliss[3]

1 School of Earth and Environmental Sciences, The University of Adelaide, Adelaide, SA; 2 Bushfire Cooperative Research Centre, Level 5/340 Albert Street, East Melbourne VIC ; 3 Department for Environment and Heritage, Mount Remarkable, SA.

Sediment erosion following a wildfire in the Mount Bold reservoir in South Australia provided an excellent case study for assessing the emergency response initiated to protect our water supply. On 10 Jan 2007 a wildfire resulted in about 1700ha being burnt including part of the Mount Bold reservoir reserve. Numerous resources were deployed to the fire including up to 400 firefighters, more than 80 appliances, water bombers and observation aircraft. The fire threatened approximately 60 homes, one dwelling was destroyed and numerous sheds, livestock and equipment sustained fire damage. Substantial widening by dozers was undertaken to various trails and backburning was conducted to eventually contain and extinguish the fire.

The Bureau of Meteorology predicted 50mm of rainfall to occur shortly after the fire. As the area was highly erodible and water quality needed to be maintained, the water supply agency, SA Water, initiated an emergency sediment trapping program. SA Water, Forestry SA and the Department for Environment and Heritage installed 53 sediment traps using a variety of structures including hay bales, geofabric bags, coir logs, silt fencing, steel droppers and jute matting. This paper focuses on the emergency response, the success of the trapping program and alternative strategies to sediment trapping for managing erosion risks following wildfire events.

1. Introduction

Water storage facilities such as the Mount Bold water reservoir in South Australia are surrounded by forests, woodlands and grassland. Where vegetation is present the inevitability of fire prevails. Emergency responses to protect water reservoirs include the initial suppression effort to contain any fire and the post-fire remediation to protect the water quality from potential ash, charcoal and sediment deposits. Previous wildfires in 2003 such as Canberra, East Kiewa valley and Ovens Basin altered the surrounding water storage catchment resulting in water quality issues (EPA 2003; Lane *et al.* 2006; Rustomji and Hairsine 2006; White 2006). In February 2009 about 30% of Melbourne's catchments were damaged by wildfire causing wide media interest in whether supplies would be adequate considering that Melbourne's water storages were only 30.2% full at the time (Melbourne Water 2009).

The South Australia Country Fire Service (CFS) suppressed the wildfire at Mount Bold reservoir reserve then the South Australian Water Corporation (SA Water) implemented an emergency sediment trapping program. This paper reviews the Mount Bold emergency response in relation to the following questions: i) Did the wildfire suppression response control the area burnt? ii) Did the emergency sediment trapping response capture the eroding sediment? iii) Was the water quality affected? and iv) What improvements and alternatives are there other than relying solely on emergency responses?

2. Study Site

The study was conducted at Mount Bold ($35^0$07’26”, $138^0$41’00”) located in the Southern Mount Lofty Ranges approximately 35 km southeast of Adelaide, South Australia (Figure 1). Land use in the area includes the Mount Bold water reservoir, forestry and various farms. The area lies in a temperate climate zone with warm, dry summers and cool, wet winters. Mean annual rainfall at Kuitpo Forest HQ is 830.2mm (BOM 2007). The topography is generally steeply sloping especially in the upper catchment areas. Soils are shallow to moderately deep acidic soils on rock, with the majority of the catchment having either high or very high water erosion potential (Soil and Land Program 2007). The vegetation is typically Eucalyptus forest and woodlands, pine plantations or grasslands.

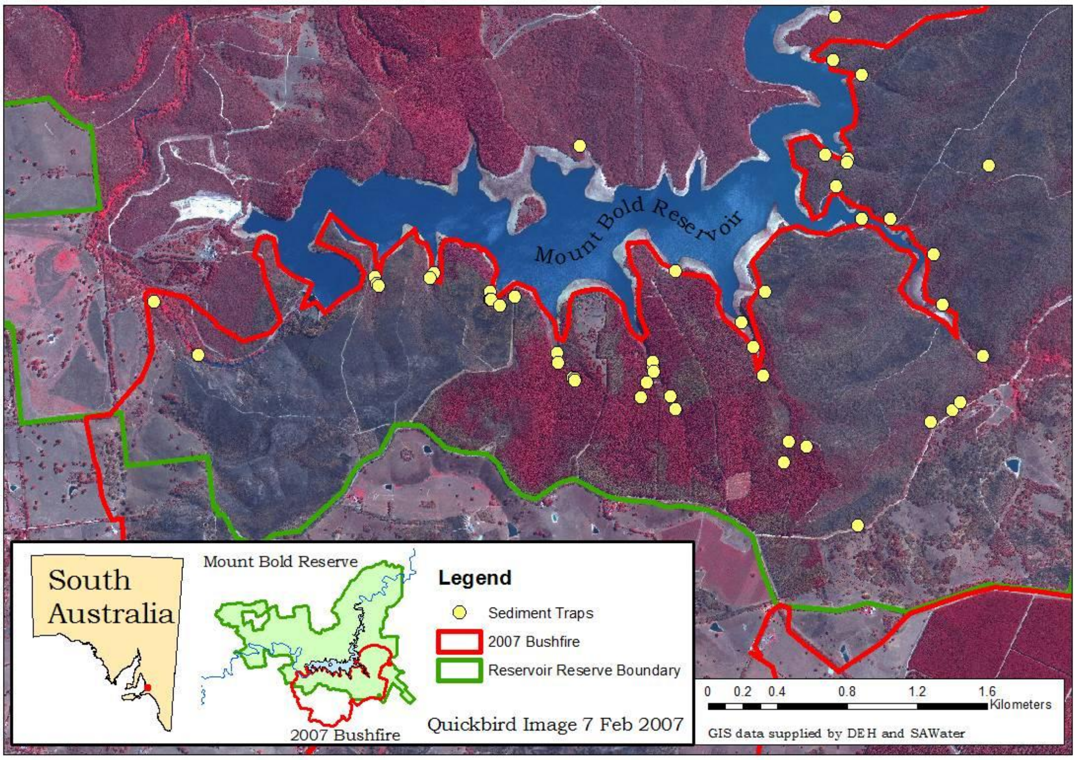

Figure 1 Location map of Mount Bold Reservoir reserve, 2007 wildfire and the sediment traps.

3. Wildfire suppression emergency response

On 10 January 2007 a wildfire commenced on land adjoining the Mount Bold Reservoir Reserve. The fire was managed by the CFS including volunteer fire fighters, staff from SA Department for Environment and Heritage (DEH), SA Water and the South Australian Forestry Corporation (Forestry SA). In total around 1700 hectares was burnt (Figure 1). Fire fighting resources included up to 400 firefighters, more than 80 appliances, water bombers and observation aircraft. One dwelling was destroyed, approx 60 home were threatened and numerous sheds, livestock and equipment sustained fire damage. Dozers were used to widen various trails and backburning was conducted to eventually contain and extinguish the fire.

The 2007 Mount Bold fire was the fourth largest fire experienced in the Adelaide Hills since Ash Wednesday in 1983 (DEH fire history GIS records). Emergency response to such an event is not an everyday occurrence. The last fire within the area covered by the Mount Bold wildfire occurred over 30 years ago with only 53ha being burnt. No prescribed burning had been conducted in this time. The cause of the Mount Bold fire was believed to be an arsonist. Based on an extreme Forest Fire Danger Index with a highest temperature of 37.10C and very high fuel levels the success of the first attack succeeding on the 10 January 2007 was 70-10% (DEH 2006). The next day weather conditions were substantially milder with temperatures only reaching 25.40C. This provided emergency fire suppression crews suitable conditions for blacking out. With the help of suitable weather conditions the emergency wildfire suppression response did manage to control the area burnt. Fire severities based on the same visual field classification described by Chafer et al.(2004) for Eucalyptus forests and woodlands ranged from extreme (all green vegetation burnt and stems <10mm thick incinerated) to low (ground fuels and low shrubs burnt).

4. Emergency Sediment Trapping Response

In response to the Bureau of Meteorology predicting 50mm of rainfall to fall shortly after the wildfire event SA Water initiated an emergency sediment trapping program. A field team of approximately 28 people were involved in the program. This team consisted of staff from SA Water and seasonal fire fighters employed by DEH. Forestry SA also installed additional traps in areas of pine plantations planned for harvest after the fire. Equipment was transported by hand, trucks and the reservoir boat. Decisions on where to erect the traps was made from an initial field inspection by local SA Water staff and an experienced contractor who had done similar work in Western Australia.

In total fifty-three sediment traps were constructed after the fire using hay bales, jute matting, coir logs and silt fencing (Morris *et al.* 2008). Coir logs were not available at the start so initially traps were built of hay. Additional traps were later built of coir logs and silt fencing. Sediment trapping success was then monitored after the first major rainfall event in Jan 07, again in April 07 then one year later. In the first six months 22 of the 53 sediment traps were considered successful, meaning that both their structural integrity was maintained and they had caught sediment. Problems identified with the other traps included inappropriate size, location, construction and animal interference. The combined 53 sediment traps managed to capture in excess of 160 cubic metres of sediment. Substantially more sediment reached the reservoir system from areas without traps or sites where the traps were not sufficient for the sedimentary processes occurring.

The failure in sediment traps could not be attributed to extreme rainfall events. Although the Bureau of Meteorology predicted 50mm of rainfall to occur shortly after the fire, actual rainfall recorded was 46mm over three days just eight days after the fire. Using rainfall intensity frequency duration analysis data from the Bureau of Meteorology Houlgraves Alert weather station, the January 2007 event was a rainfall event likely to occur within a normal year whereas the 30 April 2007 event was a typical 1 in 5 year average recurrence interval event for durations from 6 hours to 72 hours. This means that the January event is a likely occurrence after wildfires whereas the probability of the April event is much less.

5. Water Quality

The success of the sediment traps was also evaluated by assessing reservoir water quality after the fire. Initial visual observations after the first rainfall noted areas with floating charcoal and higher turbidity. Sediment had clearly entered the reservoir and some areas adjoining the traps had visible algal growth. The only measurable water quality impact that could be attributed to the effects of the fire appears to be Total Phosphorus (TP) at the offtake depth (Site 12530) reaching 0.65 mg/L. The effect was temporary as values of TP normalized, 0.04 mg/L, by the next sampling period two months later. Routine water sampling conducted near the dam wall in the middle of the reservoir (Site 1241) did not show substantially higher results after the wildfire (Figure 2). The data spikes for Turbidity in June 2005 and Total Phosphorus in October 2008 (Figure 2) were not related to the Mount Bold 2007 wildfire and at this stage there is no clear explanation as to why they spiked.

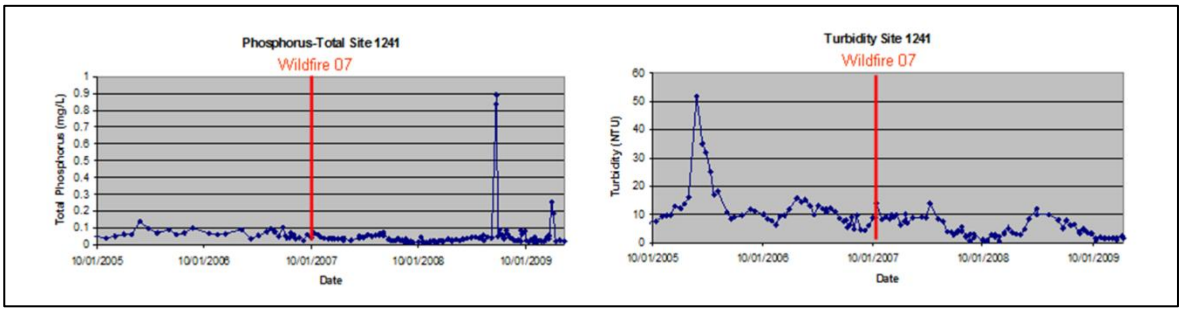

Figure 2 (LH) Total Phosphorus (RH) Turbidity at Mount Bold reservoir before and after the wildfire that occurred on 10/1/07.

Mount Bold reservoir is on the Onkaparinga River which is supplemented by piped water from the Murray River. Water from Mount Bold reservoir gravitates into the Happy Valley Reservoir via an aqueduct from the Clarendon Weir. Happy Valley filtration plant produces safe drinking water by a process of coagulation and sedimentation to remove approximately 90% of suspended particles and dissolved organic compounds that can contribute to discolouration. Filtration is used to remove the remaining particles that pass beyond the sedimentation process and then chemical dosing to fluoridate, pH correct and disinfect the final product. There was no impact from the wildfire and subsequent erosion on the Happy Valley or Mount Bold Reservoir (*pers. comm.* Centofanti 2009).

6. Improvements and alternatives to emergency responses

Improvements to emergency responses highlighted by the Mount Bold case study included pre-planning, fire operations and post-fire recovery, especially in regard to sourcing sediment trap material, trap designs and suitable trap locations. SA Water had done some pre-planning including discussion on actions to be taken in the event of fire based on previous experiences at other reservoirs; a management plan had been written; and appropriate staff were available, including experienced local crews, a dedicated fire management officer and access to the DEH seasonal fire crews. Improvements could have been made with prior identification of potential erosion problem spots and identification of suitable trap locations in the event that a wildfire occurred.

Training on various trap designs, construction and implementation would be beneficial for the regular staff. The problems associated with the traps highlighted the need to design appropriate traps for the amount of sediment movement that occurred and to accommodate the high water velocity on the steep slopes. Extensive research has been conducted in the USDA Forest Service Regions (Robichaud *et al.* 2000) on evaluating the effectiveness of post-fire rehabilitation treatments. Recommendations from this research may be applicable to Mount Bold and other Australian water reservoir reserves. Similar research in both the Adelaide Hills and other types of landforms would be beneficial to gauge the need and suitable designs of traps in these alternative areas.

Alternative management strategies include addressing fire ignition, maintaining fire-trails, the use of prescribed burning, relying on water treatment or ensuring alternative water sources are available. The wildfire at Mount Bold was believed to be lit by arson activity. South Australian police and CFS actively monitor such activity however the prevention of all arson activity is highly unlikely. Other than the public viewing area at the dam wall the Mount Bold reservoir reserve is closed to the public. The argument to keep reservoir reserves closed to reduce arson is a valid one but it will not prevent fires from entering the reserves from adjoining areas. The site of ignition for the Mount Bold wildfire was on the adjoining road edge away from the reserve.

To aid fire suppression, resources including fire crews and aircraft are needed. An adequate track/trail system is needed to access and create fire breaks. In the Mount Bold emergency response, fire suppression resources including crews and aircraft were accessed and a sufficient trail system was maintained allowing easy access for the fire fighters. The trails were widened as part of fire suppression activity and some questionable additional fire trails were installed. This trail system did enable a suitable backburn to be lit to contain and eventually extinguish the fire.

Another management strategy not used previously by SA Water at Mount Bold is prescribed burning which reduces fuel levels and subsequent fire intensities. Erosion potential is increased immediately after prescribed burning but this increase is acceptable if the burn is conducted appropriately. Understanding of fire regimes as defined by Gill (1975) will enable fire management to consider the consequence of different fire type, intensity, frequency and season. The long term impact of altering the fire regime needs consideration. If fire is excluded vegetation will provide sufficient fuel for high intensity fires whereas high fire frequency will keep the fuel levels low leaving the soil surfaces exposed. A balance is needed between the two extremes.

Spatial and temporal planning of prescribed burn locations is required in order to balance both biodiversity protection and adequate coverage of fuel reduced areas. Careful control lines can be established to enable vegetation buffers between the prescribed burn and the reservoir. Prescribed burning reduces but does not eliminate the threat of wildfire (Fernandes and Botelho 2003). Fuel reduction increases the number of days per year that successful suppression operations could be undertaken (Rustomji and Hairsine 2006) but under severe fire weather conditions fire fighters have little ability to suppress wildfires. Prescribed burning will not prevent wildfires but when combined with other management strategies can prevent the entire loss of the catchment to extreme wildfires.

Another management strategy involves relying on water treatment or the transfer of threatened water. Technology now allows for water treatment plants that are capable of dealing with high turbidity and most algal blooms. The costs of this technique can involve the addition of chemicals to the water reservoir, the need for advance filtering treatments and the long-term problems associated with potential build up of sediment within the reservoir. A recent solutions used by Melbourne Water was to transfer water out of fire affected catchments into unaffected catchments. As the water levels on 17 Feb 2009 were only 31.8% full, immediate action was required. Storage of water in different locations is a possible option to avoid complete loss from one wildfire event.

7. Conclusion

Numerous lessons were learnt from both the fire suppression efforts and the sediment trapping program at Mount Bold. We cannot rely entirely on emergency responses to protect our water reservoirs from wildfires. Wildfire suppression does not always manage to contain fires during the first attack. Recent fires during 2009 in Victoria demonstrated that suppression during extreme fire conditions is virtually impossible. In the case of the Mount Bold wildfire,1700ha was burnt over numerous days before the fire was declared safe. Accepting that water catchments will be burnt, an alternative emergency response is to initiate a sediment trapping program such as the one undertaken at Mount Bold.

The sediment trapping response captured large amounts of moving sediment, but numerous trap failures and insufficient coverage resulted in additional sediment entering the reservoir. Whilst the Mount Bold water quality was not clearly affected and the filtration system remained functional, the incident does highlight improvements and alternatives to emergency responses. The difficulties that arose with the sediment trapping program provide a clear message that planning, training and alternative strategies are required to manage water quality in relation to inevitable wildfires in our catchments. Emergency responses alone will not protect our water reservoirs.

Acknowledgements

SA Water staff, especially the Mount Bold Reservoir staff and those who helped install the sediment traps. CFS Mark Thomason for the Mount Bold fire incident reports and Linton Johnson from the Bureau of Meteorology. PhD supervisors and advisors Dr B Ostendorf, A/ Prof D Dragovich, Dr M Henderson, Prof R Bradstock and Monique Blason. Funding was provided by the South Australian Water Corporation and the Bushfire Cooperative Research Centre.

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Appendix C: Conference posters

C1 Morris R, Bradstock B, Dragovich D, Ostendorf B (2012) Managing soil erosion in the Mount Lofty Ranges, South Australia. AFAC/Bushfire CRC 2012 conference ‘Diverse country, common ground’ 28-31 August, Perth, WA, Australia.

C2 Morris R (2011) The dirt on assessing post-fire erosion. AFAC/Bushfire CRC 2011 conference ‘New world, new thinking’ 29 August – 1 September 2011, Sydney, NSW, Australia.

C3 Morris R, Bradstock B, Dragovich D, Henderson M, Ostendorf B (2010) Prescribed burning and sediment movement in the Mount Lofty Ranges, AFAC/Bushfire CRC 2010 conference ‘Same, same, but different – learning lessons in a changing world’ 8-10 September 2010, Darwin, NT, Australia.

C4 Morris R, Calliss S (2009) Does an emergency response protect our water reservoirs? AFAC 2009, ‘Meeting expectations’ 22-25 September 2009 Gold Coast, QLD, Australia.

C5 Morris R, Moncrieff J, Bradstock B, Buckman S, Connelly P, Dragovich D, Ostendorf B (2009) Terrestrial laser scanning and measurement of sediment movement following fire, 7th International conference on geomorphology ANZIAG, ‘Ancient landscapes-modern perspectives’ 6-11 July 2009 Melbourne, VIC, Australia.

C6 Morris R, Calliss S, Dragovich D, Henderson M, Ostendorf B (2008) Trapping sediment following bushfire at Mount Bold Water Reservoir, South Australia. International Bushfire Research Conference 2008 and 15th Annual AFAC Conference 1-3 September 2008, Adelaide, SA, Australia.

C7 Morris R, Dragovich D, Henderson M, Moncrieff J, Ostendorf B (2007) 3D laser scanning of sediment movement following bushfire at Mount Bold Reservoir. AFAC/Bushfire CRC 2007 conference 19-21 September 2007 Hobart, TAS, Australia.

MANAGING POST-FIRE SOIL EROSION IN THE MOUNT LOFTY RANGES, SOUTH AUSTRALIA

Rowena Morris[1,2], Ross Bradstock[2], Deirdre Dragovich[3] and Bertram Ostendorf[1]

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[3] School of Geosciences, University of Sydney, NSW

Introduction

Post-fire soil erosion can alter ecosystems by affecting water quality, soil formation and general landscape characteristics. Management options to mitigate post-fire soil erosion depend on the geomorphology, fire regime, season and rainfall characteristics. This research focuses on various case studies of differing fire types in the Southern Mount Lofty Ranges (SMLR) (Fig 1).

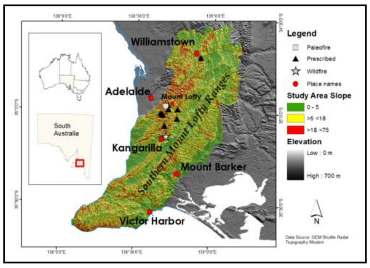

Figure 1: Location map

Paleofires

Research into the Wilsons Bog paleofire located in Cleland National Park, SA (Fig 2), established that post-fire erosion is a natural process that is sensitive to climatic variations that inturn influence vegetation cover. The analysis of charcoal in the stratigraphic soil profile recorded at least fifteen separate fire events that caused post-fire deposition during the period from 6000 years before present.

Buckman S., Brownlie K., Bourman R.P., Murray-Wallace C.V., Morris R.H., Lachlan T.J., Roberts R.G., Arnold L.J and Cann J.H. (2009) Holocene palaeofire records in a high-level, proximal valley-fill (Wilsons Bog), Mount Lofty Ranges, South Australia. *The Holocene.* 19,7,1-13.

Figure 2: Stratigraphic section at Wilsons Bog

Wildfires

Post-fire sediment movement is influence by hillslope morphology. Managers (Fig 3) can predict the likely areas of concentrated post-fire soil erosion and deposition with a good working knowledge about hillslope morphology.

Morris R., Dragovich D. and Ostendorf B. (2012) Hillslope erosion and post-fire sediment trapping at Mount Bold, South Australia. *Proceedings of Wildfire and Water Quality: Processes, Impacts and Challenges Conference*, 11–14 Jun 2012, Banff, Canada, *IAHS Publ.* 354, 42-50.

Figure 3: Installing sediment barrier traps

Prescribed fires

Sediment movement following prescribed fires depends on the fire severity, slope angle and rainfall. Based on assessment of 10 prescribed burns in the SMLR, over 50% of the 505 sites indicated post-fire sediment movement. Reducing the fire severity from high to low will reduce the likelihood of sediment movement by 52%. A simple visual assessment framework has been developed to monitor post-fire erosion.

Morris R., Buckman S., Connelly P., Dragovich D., Ostendorf B. and Bradstock R. (2011) The dirt on assessing post-fire erosion in the Mount Lofty Ranges: comparing methods. R.P. Thornton (Ed) 2011, *Proceedings of Bushfire CRC & AFAC 2011 Conference Science Day*, 1 Sept 2011, Sydney Australia, Bushfire CRC, 152-169.

End User Statement

Danni Boddington, Fire Manager, SA Water

Managing post-fire erosion is critical to healthy drinking water. SA Water has incorporated this CRC research into our ongoing management of fires in water reservoirs.

Restoration options

Typical post-fire mitigation strategies involve the use of sediment barriers (Fig 3). Based on a case study at Mount Bold of 53 sediment traps it was concluded that after a 1 in 5 year rainfall event, sediment traps will not prevent post-fire sediment movement from reaching water reservoirs (Fig 4).

Morris R., Calliss S., Frizenschaf J., Blason M., Dragovich D., Henderson M. and Ostendorf B. (2008) Controlling sediment movement following bushfire - a case study in managing water quality, Mount Bold, South Australia. *Proceedings of Water Down Under 2008 incorporating 31st Hydrology and Water Resources Symposium and 4th International Conference on Water Resources and Environment Research,*14-17 April 2008, Adelaide, Australia., 1937-1947.

Figure 4: Overflowing sediment barrier trap

Key findings

•Post-fire soil erosion is a natural process in the Southern Mount Lofty Ranges that can be influenced by differing fire management practices.

•Patterns of sediment movement are influenced by hillslope morphology.

•In the SMLR altering the fire severity from low to high during prescribed burns will increase the probability of sediment movement by 52%.

•Sediment barriers will reduce but not prevent post-fire charcoal-rich sediment and debris reaching water reservoirs after a 1 in 5 year rainfall event.

Acknowledgments: SA DENR, SA Water, SA Botanic Gardens, SA County Fire Service , SA Bureau of Meteorology, M. Henderson, S. Callis, A. Porter, S. Buckman and K. Brownlie.

CRC Australia | THE UNIVERSITY OF ADELAIDE AUSTRALIA | University of Wollongong | University of Sydney | Government of South Australia Department of Environment and Natural Resources | SA Water

THE DIRT ON ASSESSING POST-FIRE EROSION

R.H. Morris [1,2,3]

[1] School of Earth and Environmental Sciences, The University of Adelaide, Adelaide, SA. [2] Bushfire Cooperative Research Centre, Level 5/340 Albert Street, East Melbourne VIC. [3] The University of Wollongong, NSW.

Introduction

- Historical evidence indicates that fire has the potential to trigger considerable sediment movement within and from the Mount Lofty Ranges
- Environmental assessment of erosion impacts following prescribed burning in the Mount Lofty Ranges receives minimal post-fire monitoring
- Assessment of post-fire erosion requires the consideration of the event timescale, spatial extent, magnitude and frequency
- This research assesses and compares the methods used to monitor sediment movement post-fire in the Mount Lofty Ranges (Figure 1)

Conclusions

- **A combination of post-fire erosion monitoring methods is required to cover all timeframes, spatial scales, event magnitudes and frequency**
- The most appropriate method to record historical erosion is the use of stratigraphy and dating. Stratigraphy is an appropriate method for determining post-fire erosion/deposition frequency. The frequency of post-fire erosion events at the decadal to the millennial timescale is an area requiring further investigation
- Morphometric methods including terrestrial laser scanning and close range photogrammetry have improved our ability to measure sediment movement over a variety of spatial scales. These results can then be interpreted to assist in understanding micro-topography, catchment and landscape scale processes.
- When monitoring prescribed burning the use of a rapid visual assessment creates a simple, affordable system that adequately reports on event magnitude at a spatial scale that suits the validation of pre-burn environmental assessments

End User: *Shane Wiseman, Fire Management Branch, DENR, South Australia*

"This study has produced a simple classification system for post-fire erosion that considers event magnitude. Land managers can use this system to validate environmental assessments of prescribed burns and to prioritise areas that may need remediation after wildfires."

Sediment Class	Types of Evidence	Examples
1	Surface crusting Armouring Splash pedestals Small areas of wash deposits	 Splash pedestals
2	Depositional steps (<10 cm^2)(often behind vegetation) Litter dams and micro-terraces Larger areas of wash deposits (<50 cm^2)	 Litter dams and micro-terraces
3	Some concentrated flow Erosional steps/small headcuts Deposition >10 cm Colluvial fans <1m deep Drainage scouring >10 mm	 Deposition >10cm
4	Concentrated rills (>929 cm^2) Colluvial fans ≥1 m deep Debris flows <1 m wide	 Concentrated rills
5	Gullies (>1 m deep) with own side slopes Colluvial fans >5 m deep Debris flows >1 m wide	 Debris flow

Figure 2 Rapid post-fire erosion assessment
Modified from Bracken and Kirkby (2005) Differences in hillslope runoff and sediment transport rates within two semi-arid catchments in southeast Spain. *Geomorphology* **68**, 183-200

Study Site and Methods

Erosion and deposition from a Holocene paleofire at Wilson's Bog, wildfire at Mount Bold and ten prescribed burns were assessed in the Mount Lofty Ranges (Figure1)
Eight methods to measure post-fire sediment movement were trialled and compared (Figure 2,3 and Table 1)

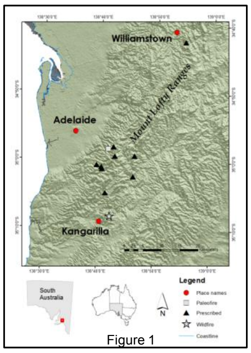

Figure 1 (Right) Location map of the paleofire, wildfire and prescribed fires assessed in the Mount Lofty Ranges, South Australia
(DEM sourced from SRTM data)

Figure 3 (Below) Field set-ups and associated equipment for monitoring onsite natural post-fire soil erosion
A) Sedimentary layers (sample bags, shovel, tape-measure) **B)** Dating (sample tubes, sample bags, dating machines, scintillation counter) **C)** Erosion Pins (metal pins, hammers, rulers) **D)** Sediment Traps (hay bales, star pickets, jute matting, hammers, shovels, numerous personnel) **E)** Water Samples (boat, jars, laboratory) **F)** Terrestrial laser scanning (laser scanner, GPS) **G)** Close range photogrammetry (field tripods, cameras, survey equipment, numerous personnel) **H)** Visual assessment (GPS, clipboard, clinometer, water dropper)

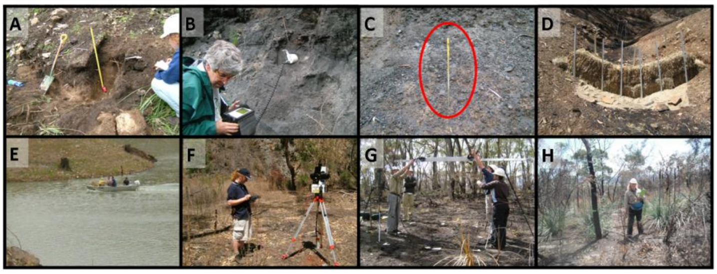

Table 1: Summary of the effectiveness of post-fire erosion monitoring methods used in the Mount Lofty Ranges in the context of timeframes, spatial scale, magnitude and frequency

Method	Event timeframe				Event spatial scale					Event magnitude					Frequency
	Short <1yr	Medium >1<10yrs	Long >10 <100yrs	Historical >100	Point	Plot	Hillslope	Catchment	Landscape	Low	Moderate	High	Very High	Extreme	
A. Stratigraphy	Y	Y	Y	Y	Y	Y	N^i	N^i	N^i	Y	Y	Y	Y	Y	Y
B. Dating	N^*	N^*	Y	Y	Y	N^i	N^i	N^i	N^i	N^*	N^*	Y	Y	Y	Y
C. Erosion pins	Y	Y	N^*	N	Y	N^i	N^i	N^i	N	Y	Y	Y	N^*	N^*	N^*
D. Sediment traps	Y	N^*	N	N	N	Y	Y	N^i	N	Y	Y	Y	N^*	N^*	N^*
E. Water samples	Y	Y	Y	N	Y	N^*	N^*	Y	N^i	N	N	N^*	Y	Y	Y
F. Laser scanning	Y	N^*	N^*	N	Y	Y	Y	N^i	N^i	N^*	Y	Y	Y	Y	N^*
G. Close range photogrammetry	Y	N	N	N	Y	Y	N^i	N	N	Y	Y	Y	N^*	N^*	N^*
H. Visual analysis	Y	Y	N^*	N	Y	Y	Y	N^*	N	Y	Y	Y	Y	Y	N

Y = Yes, methods is suitable: N = No, method is not suitable
N^* In some cases if the materials or experimental design are modified it may be possible to use this method
N^i Larger areas can be obtained by interpreting the results

Acknowledgements
PhD supervisors Bertram Ostendorf, Deirdre Dragovich, Meredith Henderson, Ross Bradstock. Paleofire research conducted by Collin Murray Wallace, Bob Bourman, Sol Buckman and Katherine Brownlie. Terrestrial laser scanning conducted by Maptek Pty Ltd. Close range photogrammetry research conducted by Paul Connelly and UniSA students. Project advice and sediment trap installation provided by staff from South Australia Water and South Australian Department of Environment and Natural Resources. Funding from Bushfire CRC and Native Vegetation Grant.

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PROGRAM B

PRESCRIBED BURNING AND SEDIMENT MOVEMENT IN THE MOUNT LOFTY RANGES, SOUTH AUSTRALIA

R.H. Morris[1, 2] R. A. Bradstock[2], D. Dragovich[3], M. Henderson[4], B. Ostendorf[1]

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2 Centre for Environmental Risk Management of Bushfires, University of Wollongong, New South Wales
3 School of Geosciences, University of Sydney, New South Wales
4 Science Resource Centre, Department of Environment and Natural Resources, South Australia

Introduction

- Land managers in South Australia are required to consider erosion as part of their environmental assessment for prescribed burning
- Currently the main concern expressed in DEH environmental reviews is if slopes are greater than 18 degrees
- In the case of Mount Lofty most prescribed burn sites will encompass slopes greater than 18 degrees
- This study concentrates on prescribed burning conducted within 40km of Adelaide (34⁰57'S,138⁰31'E) to determine if sediment movement occurs post prescribed fire and what factors, such as slope angle, influence the amount of movement

Methods

- Sediment movement was assessed following ten prescribed burns in the Mount Lofty Ranges, South Australia
- 505 site assessment were made recording sediment class, fire severity, vegetation cover, soil properties, bioturbation and topography
- Fire severity classifications were based on visual descriptions described by Chafer *et al.* (2004)
- Sediment movement features were grouped into classes using a modified version of the morphological runoff zones described by Bracken and Kirkby (2005)

Class 1 Pedastools Large Deposits | **Class 2** Micro-terraces | **Class 3**

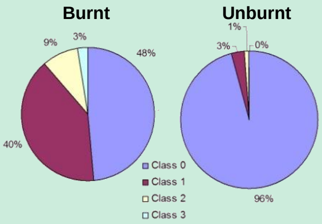
Examples of sediment movement classes

"This study will assist our environmental assessment process for prescribed burning through an improved understanding of the factors that influence sediment movement post fire in the Mount Lofty Ranges. A greater understanding of erosion will lead towards better environmental guidelines for prescribed burn planning."

Ian Tanner
Senior Regional Fire Management Officer, DENR SA.

Key findings

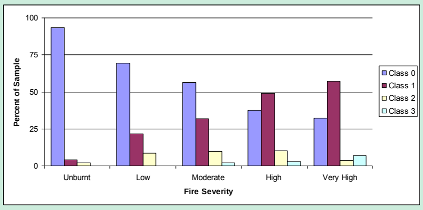
- The main controlling factor of sediment movement was the presence of fire (only 4% of unburnt sites showed evidence of sediment movement compared with 52% of burnt sites)



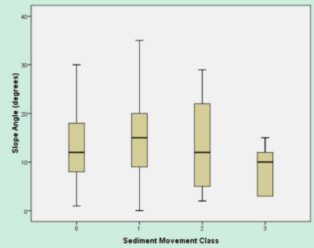
Percentage of sediment movement classes
Burnt n=342
Unburnt n=163

- Sediment movement was greater at sites with either a high or very high fire severity

Percent of sediment movement classes by fire severity
Sample Numbers
UB n=184
L n=23
M n=103
H n=167
VH n=28



- Slope is less important than fire severity
- Rainfall duration and intensity influences the amount of sediment movement
- Class 3 sediment movement rarely occurred following prescribed burning and did not occur in monitored unburnt sites



Sediment classes in relation to slope angle

Outcomes

Results from this research are being compiled to provide guidelines on assessing for erosion impacts from prescribed burning. Guidelines will include fire severity, slope and rainfall.

References

Bracken and Kirkby (2005) Differences in hillslope runoff and sediment transport rates within two semi-arid catchments in southeast Spain. *Geomorphology* **68**, 183-200

Chafer CJ, Noonan M, Macnaught E (2004) The post-fire measurement of fire severity and intensity in the Christmas 2001 Sydney wildfires. *International Journal of Wildland Fire* **13**, 227-240.

Acknowledgements DENR, SA Water, Botanic Gardens, CFS, Bureau of Meteorology and CFS promotion unit

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DOES AN EMERGENCY RESPONSE PROTECT OUR WATER RESERVOIRS?

R.H. Morris[1,2] and S.Calliss[3]

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Background

- Bushfires in water reservoir catchments can initiate water quality problems
- Australian water reservoirs are surrounded by flammable vegetation
- Bushfires have and will continue to occur in water reservoir catchments
- Water supply is an important issue as demonstrated by the recent media interest following the Melbourne 2009 Fires

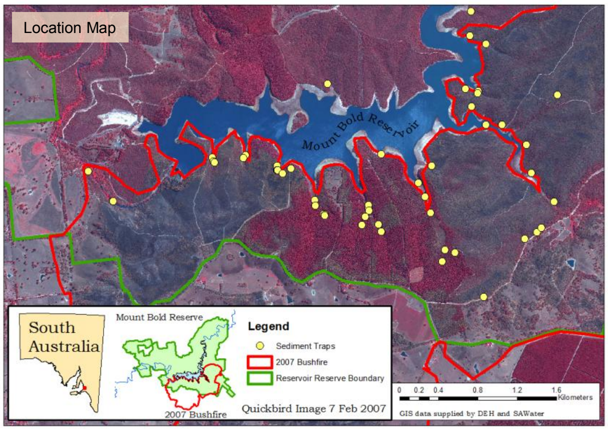
Media Headlines

Fire-affected catchments emptied to save water supply *ABC TV 16/2/09*
Bushfires contaminate Melbourne's water supplies *Herald newspaper 17/2/2009*
Fires could rob Melbourne of water for decades to come *ABC local radio 18/2/09*


Mount Bold Reservoir

Mount Bold Water Reservoir Case Study

Mount Bold is located 35 km south of Adelaide (138⁰41'30''E, 34⁰58'0''S). Mount Bold reservoir stores water for the Happy Valley water treatment plant that supplies potable water to the city of Adelaide.



Australian Case Studies

Case studies of fire affected water reservoir from around Australia were reviewed including 2001 Sydney Fires, 2003 Canberra Fires, 2003 Victorian Fires 2009 Melbourne Fires


Failed Sediment Trap

Alternatives to emergency responses

Whilst bushfire are an inevitable part of managing Australian water reservoirs, there are numerous alternative management strategies. These include

- •Advanced water treatment plants
- •Prescribed fire
- •Fire ignition management
- •Diverting water

Fire Suppression

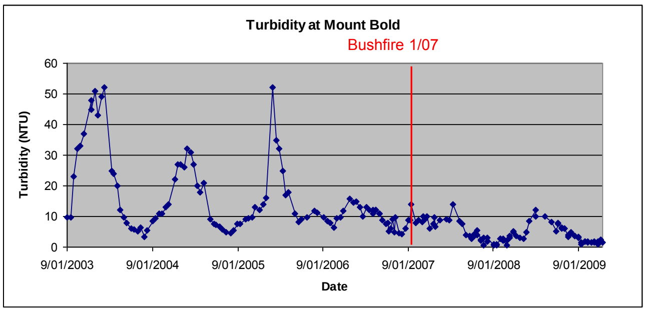
- Fire was ignited (10 Jan 2007) during extreme fire weather conditions with temperatures reaching 37.1˚ C
- The next day suppression was aided by milder conditions with temperatures only reaching 25.4˚ C
- The entire water supply catchment was not burnt due to the milder conditions allowing fire suppression efforts to be effective

Sediment trapping

- SA Water installed 53 sediment traps
- In April 2007 a 1 in 5 year rainfall event occurred
- Over 130 cubic meters of sediment was caught by the traps
- Over 49% of sediment traps had problems

Water treatment

- Water samples indicated that no water quality problems occurred. There was a slight raise in total phosphorus but the effect was temporary as values normalised by the next sampling period.
- The water treatment plant at Happy Valley copes with turbidity levels as high as 250NTU. After the fire, turbidity levels only reached 14NTU at Mount Bold.



Conclusion

Based on Australian case studies it is unlikely that all emergency responses will protect water reservoirs from bushfires. In the case of Mount Bold the emergency response assisted protection by reducing the fire extent and capturing some of the sediment.

Acknowledgements: SA Water, CFS, Bureau of Meteorology and PhD supervisors Dr B Ostendorf, A/ Prof D Dragovich, Dr M Henderson and Prof R Bradstock

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TERRESTRIAL LASER SCANNING AND MEASUREMENT OF SEDIMENT MOVEMENT FOLLOWING FIRE

R. Morris[1,2], J. Moncrieff [3] R. Bradstock [2,4], S. Buckman [4] , P. Connelly [5], D. Dragovich [6], B.Ostendorf [1]
1. University of Adelaide, South Australia 2. Bushfire Cooperative Research Centre, Victoria 3. Maptek, Glenside, South Australia 4. University of Wollongong, New South Wales 5. University of South Australia, South Australia 6. University of Sydney, New South Wales
Corresponding author R. Morris rowena.morris@adelaide.edu.au

Introduction

- Quantitative measurements are required to adequately assess erosion post-fire.
- Maptek I-Site laser scanning provides a relatively new technique that allows both spatial and temporal acquisition of topographical data.
- The aim of this research was to evaluate the use of terrestrial laser scanning (TLS) for post-fire erosion assessment.

Methods

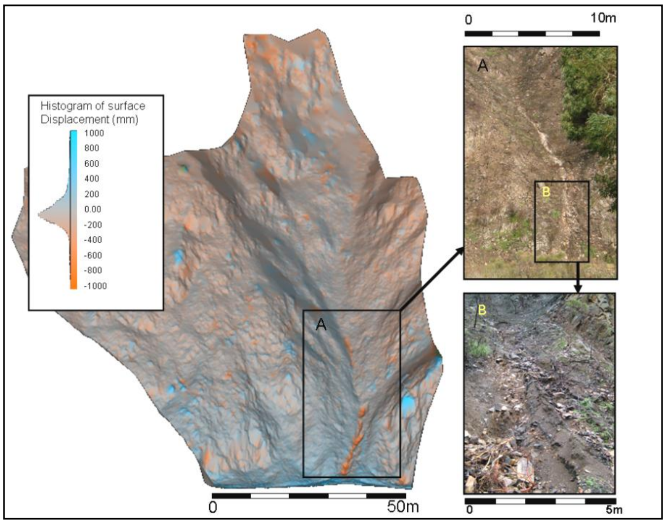
- Following a wildfire in January 2007 erosion was measured using a Maptek I-Site 4400LR terrestrial laser scanner at Mount Bold Water Reservoir, South Australia.
- This technique was compared with other traditional techniques including visual observation, erosion pins, sediment traps, photogrammetry, water quality parameters, tracers and airborne laser scanning.

Results

- Field time took only two days using TLS
- Equipment was heavy 14kg, but this was comparable to other techniques
- Surface models were derived from the data
- Surface displacement models provided greater surface coverage than other traditional techniques

Above: *Sediment trap*
Below: *Digital Close Range Photogrammetry*

***Above:* *(L)* Maptek I-Site 4400LR terrestrial laser scanner *(R)* Erosion pin**
***Below:* Modelled surface representing volume change between Feb 07 and May 07 based on a 1m signed surface difference. Inserts are photos from field site.**



Discussion

Advantages

- Data capture is relatively easy with a simple tablet computer interface
- A single operator can manage the system
- Area covered by a single scan is up to 700m which is substantially greater than a single point of an erosion pin or sediment trap
- Repeat scans can be taken without interfering with the natural processes.
- Volume measurements can be derived using Maptek I-Site Studio software
- No sediment laboratory work required
- Volume measurements are possible in previously inaccessible steep terrain

Limitations

- TLS are expensive but the price is becoming more affordable as technology and use increases. Hiring is an option
- Expert data processing is required, however I-Site Studio has simplified this process
- Six months after fire, vegetation regrowth limits the success of TLS

Acknowledgements: SA Water staff, especially Shayne Calliss and DEH staff.

Conclusion

Compared to other previous traditional survey methods terrestrial laser scanning can provide increased spatial and temporal data acquisition for interpreting surface sediment transfers with minimal interference.

PROGRAM B 3.1 IMPACTS OF FIRE ON ECOLOGICAL PROCESSES AN D BIODIVERISTY

TRAPPING SEDIMENT FOLLOWING BUSHFIRE AT MOUNT BOLD WATER RESERVOIR, SOUTH AUSTRALIA

R.Morris[1,2], S Calliss[3], D. Dragovich[4], M. Henderson[2,5] and B. Ostendorf[1]

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Introduction

•Mount Bold is located 35km SE of Adelaide, Australia

•Bushfire occurred 11 Jan 07 burning 1700ha including part of the water reservoir reserve at Mount Bold (Figure 1)

•Total of 53 sediment traps installed using hay bales, coir logs and silt fencing (Figure 1)

•Emergency sediment traps installed due to predicted rainfall of 50mm

•After the fire 748.4 mm of rain fell in the year of 2007 at Mount Bold

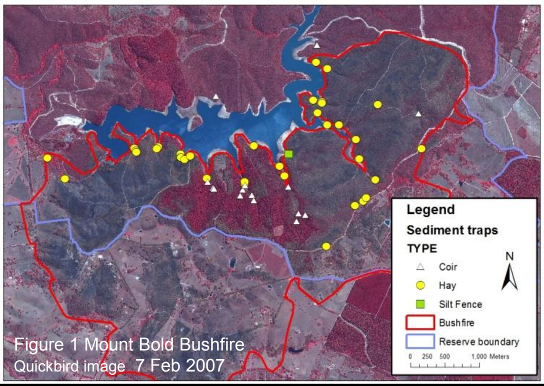

Figure 1 Mount Bold Bushfire
Quickbird image 7 Feb 2007

Figure 2 (LH) Algal growth adjoining hay bale sediment trap
Figure 3 (RH) Destroyed trap on steep slope

Results

•Over 130 cubic meters of sediment caught by the traps

•Over 49% of sediment traps had problems

•Water quality sample analysis from one site indicated no impact by the bushfire. Visual observations differ, showing turbid water and algal growth occurring in areas away from the sampling site (Figure 2)

Figure 4 (Above) Hay bale traps pre, during and post reservoir water level rise.
Figure 5 (LH Below) Traps needed to be larger than the creek channel

Key Findings

•Steep narrow slopes require stronger traps such as rock gabions (Figure 3)

•Submerged traps still collected sediment

(Figure 4)

•Wildlife destroy hay bales by eating the hay and creating homes in the traps

•Geotextile bags provide extra support and lengthen the life of hay bales

•Coir logs lasted much longer than hay bales

•Generally traps needed to be higher and wider than the existing creek bed (Figure 5)

•Silt fence required more support and additional fences to prevent the collapse (Figure 6)

Figure 6a Silt trap before

Figure 6b Silt trap after

Acknowledgements: Authors would like to thank SA Water staff, especially Monique Blason, Jacqueline Frizenschaf , Richard Munn, John Bormann, Bert Eerden, the Mount Bold Reservoir staff and the crews that installed the traps.

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PROGRAM B 3.1 IMPACTS OF FIRE ON ECOLOGICAL PROCESSES AND BIODIVERSITY

3D LASER SCANNING OF SEDIMENT MOVEMENT FOLLOWING BUSHFIRE AT MOUNT BOLD RESERVOIR

R. Morris[1], D. Dragovich[2], M. Henderson[3], J. Moncrieff[4], B. Ostendorf[1]

1. School of Earth and Environmental Science, University of Adelaide, South Australia 2. School of Geosciences, University of Sydney, New South Wales
3. Science and Conservation, Department for Environment and Heritage, South Australia 4. I-SiTE Pty Ltd, Glenside, South Australia

Aim

- Trial the use of 3D laser scanning to quantify and model sediment movement along differing slopes after a bushfire at Mount Bold Reservoir, South Australia

Location: Mount Bold

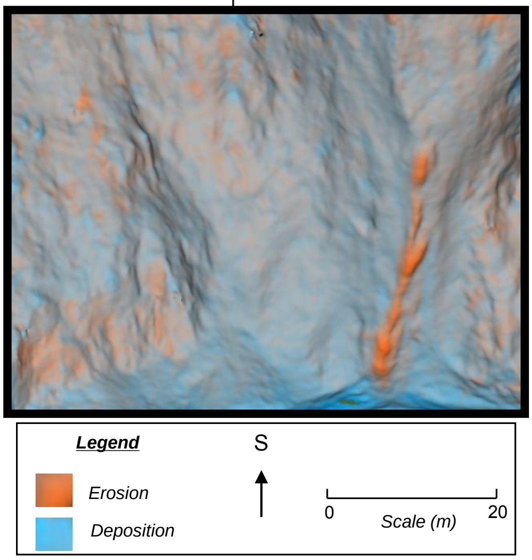
Study site

- Mount Bold Reservoir, southeast of Adelaide, South Australia
- Soils are predominantly shallow on rock, with native vegetation cover or pine plantations

Above: I-SiTE 4400LR laser scanner

Key findings

- Measurement of sediment displaced and deposited on steep slopes was possible using 3D scanned images
- Sediment was derived predominantly from gully systems along the slopes
- Colluvial fans formed at the footslopes feeding directly into the tributary



Above: Using 3D triangulation the volumetric difference map was generated using data scanned on 6 February and 22 May 2007. This data enabled volume calculations of both eroded and deposited sediment.

Above: Steep slope after the first rainfall February 2007

Above: Steep slope after the second major rainfall May 2007. This rainfall resulted in surface change of over 1m.

Methods

- Measure sediment movement using metal erosion pins and I-SiTE 4400LR scanner
- Capture images and measurements from both steep and gentle terrains
- Model and analyse images using I-SiTE Studio
- Measure erosions pins using rulers and callipers

Potential Applications

- 3D laser scanning allows technical users to visualise, measure and process rich scan data
- Volume measurements are possible in previously inaccessible steep terrain
- Improved detail enables researchers to understand the erosion processes occurring along hill slopes
- Improved information will assist the decision process of where to construct post-fire sediment control structures

Acknowledgements: Authors would like to thank I-SiTE Pty Ltd for scanning and processing numerous images and SA Water staff, especially Monique Blason, Shayne Calliss, Jacqueline Frizenschaf , Bert Eerden and the Mount Bold Reservoir staff. We would also like to acknowledge the bushfire photos from the CFS promotion unit.

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Appendix D: Fire note and case study

D1 Bushfire CRC (2010) Protecting our water reservoirs with sediment traps.

D2 Maptek (2009) Case Study: Measuring sediment movement

Copyright details:

Background briefings on emerging issues for fire managers from AFAC and Bushfire CRC.

bushfire CRC afac

FIRE NOTE

ISSUE 55 MARCH 2010

PROTECTING OUR WATER RESERVOIRS WITH SEDIMENT TRAPS

CONTEXT

This study aimed to investigate the rehabilitative effectiveness of three different sediment traps – hay bales, coir bales and silt fencing – in reducing the amount of mobilised sediment reaching the water reservoir after a bushfire.

BACKGROUND

Bushfires reduce vegetation cover and alter soil properties, which often results in the ensuing erosion being a management concern for drinking water reservoirs. After rainfall, ash, charcoal and sediment can be washed into the reservoir, affecting the water quality by altering the turbidity, taste and odour of the drinking water and by adding additional nutrients. Sediment traps are used as an emergency response after fire to capture mobilised sediment to reduce potential contamination of water reservoirs. In 2007 a bushfire occurred at Mount Bold reservoir, located 35 km southeast of Adelaide, South Australia. The reservoir is managed by SA Water (the South Australian Water Corporation), which had witnessed erosion and subsequent water quality problems in ACT reservoirs following the Canberra 2003 fires. Following a bushfire in January 2007, SA Water undertook immediate restoration action at Mount Bold using sediment traps. This provided the Bushfire CRC an opportunity to study the effectiveness of these traps. Fifty-three sediment traps were installed and monitored at Mount Bold to capture mobilised sediment from rainfall events following the bushfire in January 2007. Research has also been conducted on older fires (Holocene paleofires), dated approximately between 600 to 6000 years ago, and recent prescribed fires in the Mount Lofty Ranges, South Australia, in order to better understand post-fire erosion.

BUSHFIRE CRC RESEARCH

This Bushfire CRC PhD research project monitored the success of the trapping program by assessing the sediment structures, measuring the captured sediment and analysing the geomorphogical change, that is, change in the landform surface. Methods used at Mount Bold included erosion pins, sediment traps and terrestrial laser scanning (see 'Definitions' box). Three types of

▲ Mount Bold Reservoir after the 2007 bushfire

SUMMARY

The impact that the erosion of sediment after bushfires has on the quality of drinking water in reservoirs is of crucial concern. Emergency rehabilitation such as sediment trapping in Australian water catchments need to be monitored post rainfall to assess their effectiveness in protecting our water reservoirs. This research provides guidance on the type of sediment traps to use depending on expected runoff velocity, cost, ease of construction and duration required. Importantly, follow-up monitoring and maintenance is necessary for all sediment traps tested as traps alone cannot guarantee against reduced water quality through sediment movement following bushfires.

ABOUT THIS PROJECT

This research is part of project B 3.1: Impacts of Fire on Ecological Processes and Biodiversity, within Program B: Managing Prescribed Fire in the Landscape. For more information about this project contact: rowena.morris@adelaide.edu.au

The author: Rowena Morris (right) is a PhD candidate at The University of Adelaide and the recipient of a Bushfire CRC scholarship.

Table 1: Comparison between the three different types of sediment traps used at Mount Bold.

	ADVANTAGES	DISADVANTAGES
Hay Bales 	• Simple to install • Inexpensive – cheapest of the three options • Fast to construct • Easily transported • Easily obtained • Material decomposes • Simple removal	• Not suitable for high velocity water • Can introduce weeds* • Eaten by fauna* • Last for a short time frame (6 months)* • Needs monitoring and maintenance
Coir Bales 	• Very simple to install • Very fast to construct • Does not introduce weeds • Easily transported • Lasts for a reasonable time-frame (1.5 to 3 years) • Material decomposes • Simple removal	• Not suitable for high velocity water • Not always quickly available • Needs monitoring and maintenance
Silt Fencing 	• Can deal with high velocity water • Does not introduce weeds • Can trap large amounts of sediment depending on trap size • Material can be stockpiled ready for an emergency response	• Slow construction • Trap construction is not simple • Requires trenching to install which disturbs the site • Material does not decompose • Complex removal • Needs monitoring and maintenance

** Geotextile Bags were filter bags that the hay bales were placed into. They remove silt from water. The geotextile bags at Mount Bold minimised weed spread, prevented fauna damage and extended the life span of the bales. They add considerably to the cost of hay bales traps and the speed of installation.*

sediment traps were compared: hay bales, coir bales and silt fencing (see table this page). Geotextile Bags were trialled at three of the hay bale trap locations.

Thirty-four hay bale traps were installed by SA Water due to its concerns about potential serious erosion following a predicted 50mm rainfall event. A further 18 coir traps and one silt fence trap were also installed for comparisons with the hay bale traps. The coir material arrived after the first rainfall event. Problems with 27 of the hay bale traps were attributed to inappropriate size (48 per cent), wrong location (30 per cent), poor construction (15 per cent) or wildlife interference (seven per cent). The coir traps lasted longer than the hay bales with only two being considered unsuccessful at retaining sediment. The silt fence was not strong enough to hold a one in five-year rainfall event and subsequently failed in the middle section, however it still managed to retain the second highest volume of sediment, measuring 22m^3. Sediment traps located in two unburnt control sites were not subjected to any mobilised sediment. After one year, substantial vegetation regrowth occurred in the burnt area and sediment transfer was dramatically reduced.

DEFINITIONS

Paleofire: fires from our past.

Photogrammetry: obtaining reliable measurements by means of photography.

Pyrocolluviation: fire induced valley-fill aggradation. This means the build-up of charcoal-rich sediment at the bottom of a valley due to hillslope erosion following fires (see photos page 4).

Rock gabion: a fortification cylinder filled with rocks.

Terrestrial laser scanning (TLS): land based surveying using laser technology that creates highly accurate 3D data (See photo page 3).

After the first rainfall, visual observations of the water reservoir found areas with floating charcoal and higher turbidity. Sediment had clearly entered the reservoir and some areas adjoining the traps had visible algal growth. Water samples taken from near the dam wall did not appear to be adversely affected, based on the routine water sampling conducted by SA Water. The water required no additional filtration or treatment following the bushfire. More extensive water sampling would be needed to conclude that the bushfire had no impact on the water quality.

RESEARCH OUTCOMES

An assessment of the sediment traps at Mount Bold Reservoir found that over half the traps had problems due to their size, material and location. Large amounts of sediment breached the traps and entered the water reservoir system even though 160m^3 of sediment was captured. With improved knowledge the right trap can be used for the right location. This requires understanding about the topography, soil type, fire severity, rainfall characteristics, potential water velocity and sediment load. The sediment traps used at Mount Bold are really only effective for low velocity water. Rainfall amounts after the bushfire at Mount Bold resulted in water velocities and sediment loads that really required other structures such as rock gabions (see 'Definitions'). The rainfall events that did damage the traps were normal yearly events. The one in five-year rainfall event caused considerable damage to both the silt and hay bale traps.

This research validates the notion that rainfall following bushfires will cause erosion. Substantial sediment transfer occurs during a

END USER STATEMENT

"SA Water complies with the 2004 Australian Drinking Water Guidelines 'source to tap' approach to drinking water quality, which acknowledges the importance of sustainable land management as a key barrier to preventing contamination. Uncontrolled bushfires have the potential to contaminate our reservoirs by increasing sediment and nutrient loads, leading to turbidity and algal problems. Rowena's research has given us a good understanding of what to expect after a fire in terms of sediment movement and what measures we can take to mitigate potential water quality risks. Specifically, her work has been incorporated into a draft Fire Recovery Strategy for the Mount Lofty Ranges watershed."

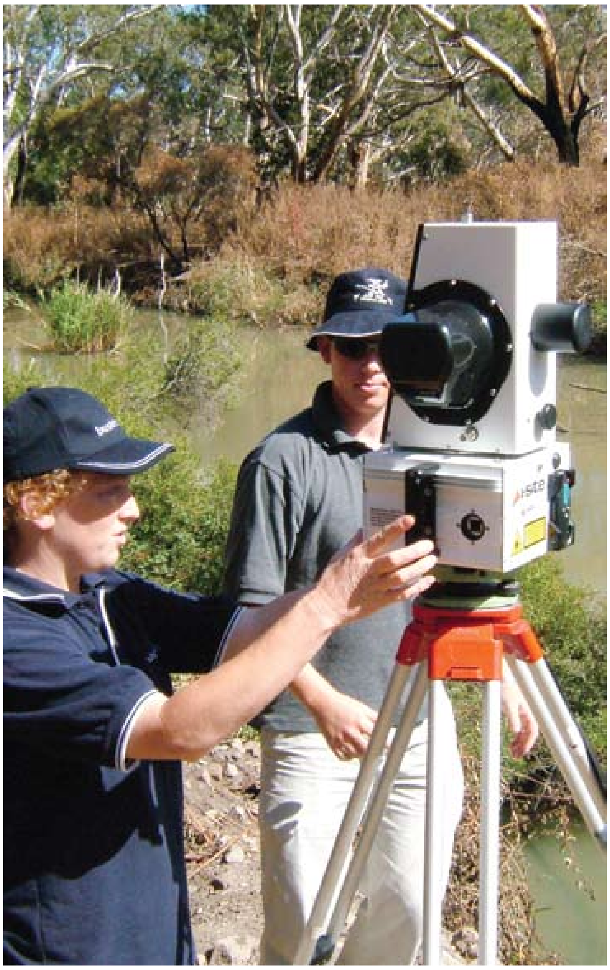
– Dani Boddington, Fire Management Officer, SA Water.

one in five-year rainfall event. Both paleofires and current fires result in rapid build-up of charcoal-rich sediment at the bottom of a valley due to hillslope erosion, referred to as pyrocolluviation (see 'Definitions' box). In places with steep slopes greater than 35 degrees, gravity alone is enough to move rocks and sediment. Erosion is a problem immediately after the fire and before the vegetation has had a chance to regrow and stabilise the soil surface. This means that any emergency sediment trapping program needs to be implemented immediately after the fire and before the first substantial rainfall event.

Due to the numerous trap failures, this research indicates that we should not rely entirely on an emergency response to capture the sediment but we should also be investigating alternatives such as advanced water filtration systems, catchment water transfer options, prescribed burning, improved planning and ignition management.

HOW THE RESEARCH WAS USED

The results of this research were used after the Victorian 2009 fires, when large areas of water reservoir catchments were burnt. Around 30 per cent of Melbourne's catchments were damaged by fire. After these fires the Australian Water Association and Melbourne Water invited the Bushfire CRC to present at an online seminar, entitled 'Fire and Water Quality'. This seminar was organised to share the range of post-fire experiences in water catchments across Australia. The experience at Mount Bold in relation to capturing sediment was appreciated by land managers and many consultants in the water business.



Researcher Rowena Morris and James Moncrief, from Maptek, operating the terrestrial laser scanner.

The Bushfire CRC has been working directly with the South Australian Water Corporation. Many presentations have been made to staff and research was made available for the Fire Recovery Strategy that was, at time of writing, being finalised by SA Water.

At the 2009 International Geomorphology Conference in Melbourne, delegates were interested in the new technique of terrestrial laser scanning for assessing post-fire sediment movement. The application of this method provides new three-dimensional data to improve our understanding of post-fire erosion. The Bushfire CRC worked closely with Maptek in trialling this technique.

FURTHER READING

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FIRE NOTE

FUTURE DIRECTIONS

Part of this research trialled terrestrial laser scanning (TLS: see 'Definitions' box). TLS enables researchers to capture high-resolution temporal and spatial data sets to assess post-fire erosion. The novel approach of this method at Mount Bold provided entire hillslope data in previously inaccessible terrain. The data assists in interpreting where and how the sediment moves following fire. This project is still analysing the TLS data in relation to the sediment traps.

A future focus for this project will be comparing the effect of prescribed burning on post-fire sediment movement with the substantial erosion following the Mount Bold bushfire. Erosion from prescribed fire is being assessed by using erosion pins, close-range photogrammetry (see 'Definitions' box), and rapid visual assessments.

Future directions to measure the effectiveness of sediment traps in reducing adverse effects on water quality needs an extensive dry and wet water sampling program that assesses routine sampling sites, sites adjoining sediment structures and control sites away from sediment structures. This information, combined with mitigation studies from other water reservoirs, can then be used to further our understanding on the effectiveness of sediment structures protecting our water reservoirs.

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▲ Before and after the April 2007 rainfall event. Pyrocolluviation overtopped the hay bales.

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AFAC is the peak representative body for fire, emergency services and land management agencies in the Australasia region. It was established in 1993 and has 26 full and 10 affiliate members.

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