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.

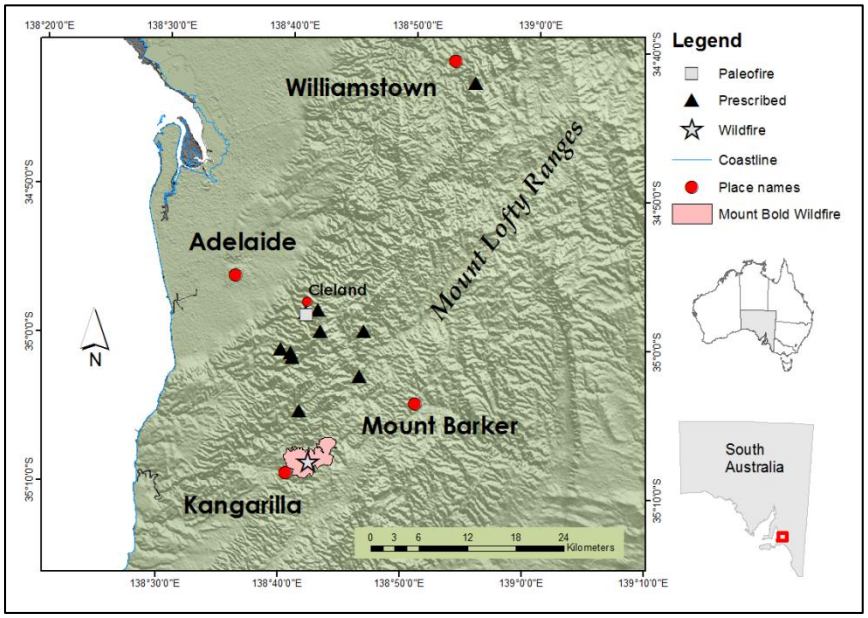

Fig. 1. Location map of the paleofire, wildfire and prescribed fires assessed in the Mount Lofty Ranges, South Australia. (DEM sourced from Shuttle Radar Topography Mission data)

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.

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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