Soil Erosion Following Wildfire in Royal National Park, NSW

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Soil losses from a sandstone catchment in the Royal National Park, south of Sydney Australia, were recorded regularly for 12 months following a wildfire on 9th January 1983, then irregularly for 6 years. High intensity, drought-breaking rains in mid March 1983 resulted in significant overland flow that eroded both ash and sand from the hillslopes as well as from fire trails and walking tracks. Large volumes of sand and debris were carried from the slopes into the streams and deposited in Port Hacking. Serious downstream flooding damaged houses and bridges.

Soil losses by the end of March (day72) ranged from 28.4 to 45.9 t ha^{-1} and by the end of the first year they ranged from 39.6 to 64.2 t ha^{-1}. This compares with 2.5 to 8 t ha^{-1} reported from similar terrain north of Sydney during a relatively dry year. Soil flux rates remained at 9.7 kg m^{-1}y^{-1} by the end of the first year. Litter cover did not change markedly in the first year after the initial leaf drop and most cover recovery was in the 0-0.5 m stratum. Similar high rainfall events 3.5 years after the fire produced minimal erosion of 0.25 to 2.19 t ha^{-1}. Monitoring continued until another fire in 1994.

The results of this study highlight the importance of the more extreme rainfall events as erosive agents. The high rates of soil erosion have implications for management of sandstone catchments around Sydney.

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KEYWORDS: bushfire, sandstone catchment, soil erosion, soil loss, Sydney, wildfire

INTRODUCTION

Research into post wildfire soil erosion has mainly come from the western United States, the Mediterranean (Shakesby and Doerr 2006; Shakesby 2011) and south eastern Australia (Wallbrink et al. 2004; Shakesby et al. 2007). In recent years researchers have described field observations after fires (Shakesby et al. 1996; Zierholz et al. 1995) and reported on catchment scale hydrologic changes (Collings and Ball 2003; Mayor et al. 2007; Smith et al. 2011a), some using fallout radionuclides to trace sediment sources (Wilkinson et al. 2007, 2009; Blake et al. 2009; Smith et al. 2011b) and mineral magnetic analysis to trace sediment provenance (Blake et al. 2006). They have investigated the impacts of fire on soil properties such as hydrophobicity (Doerr et al. 2006; Woods et al. 2007; Malkinson and Wittenberg 2011) and applied remote sensing techniques (Chafer 2008; Fox et al. 2008) and the revised universal soil loss equation to model anticipated soil losses (Yang et al. 2011). There have also been a number of literature reviews both in Australia (Wallbrink et al. 2004; Shakesby and Doerr 2006; Shakesby et al. 2007) and in the Mediterranean context (Shakesby 2011).

Few plot scale studies have measured the rates of soil erosion following wildfires on the ground, and few have been long term studies. There have been a limited number of studies in sandstone catchments around Sydney, despite these bushlands constituting large tracts of land around important water supply catchments, peri-urban recreational areas and national parks. In the catchment of Narrabeen Lagoon during a relatively dry year, Blong et al. (1982) measured from 2.5 to 8.2 t ha^{-1} of soil loss over 12 months with a high proportion of this moving in a single storm 47 days after the fire. They measured charcoal contents falling from 25% to about 10% after a few months and estimated that the soil loss in an average rainfall year would be about 20 t ha^{-1}. Dragovich and Morris (2002) used both closed plots and open plots for six months following a fire at Faulconbridge in 1994.

This was also a drought year with only 258 mm of rain falling in the 6 month study period. Consequently they recorded average soil losses from slope wash of only 1.02 t ha^{-1} and a maximum of 2.2 t ha $^{-1}$. At these low levels, bio-transferred sediment represented 36% of total sediment recorded. Prosser and Williams (1998) measured sediment flux in open troughs at Sandy Point also during a relatively dry year with only 363 mm of rain in the first 10 months after the fire. In this time they recorded sediment flux ranging from 0.07 to 1.44 kg m^{-1}. In Victoria, after an Ash Wednesday fire, Leitch el al. (1983) reported the equivalent of 22 t ha^{-1} of ash and loose soil washed from a 35 ha catchment in an intense thunderstorm but didn't isolate the soil component. The post fire erosion results from the Sydney area during dry years are similar to those observed generally in the Mediterranean where plot scale studies record first year soil losses ranging from < 1 to 10 t ha^{-1} (Mayor et al. 2007; Shakesby 2011).

A wildfire in the northern part of Royal National Park on 9th January 1983 burnt out an area of 377 ha of bushland and, although relatively minor compared to the fires that swept through the park in 1994 and 2001 (McGhee 2003; Zierholz et al. 1995; Shakesby et al. 2007), it provided an opportunity to measure, in the field, the initial rate of soil loss following a wildfire in a sandstone catchment, the relationship between rainfall, soil loss and vegetation cover and, by continuing the study over an extended period, the time for these soil loss rates to return to pre fire conditions. The study benefited from the fact that there were high intensity drought breaking rains 10 weeks after the fire and that there were a series of similar magnitude rainfall events during the following years, after background groundcover conditions had re-established.

LOCATION AND METHODS

The study was undertaken in the 40 ha catchment of Campbells Creek, immediately to the west of Grays Point, a southern suburb of Sydney (Fig 1). The centre of this catchment is located in the Royal National Park at 34^{o}03'11"S, 151^{o}04'17"E. The terrain is typical of the Hawkesbury soil landscape described by Chapman and Murphy (1989) and Hazelton and Tille (1990) consisting of benched slopes of horizontally bedded Hawkesbury Sandstone. As the elevation of this part of the park is less than 100 m, valley incision is not pronounced. Therefore slopes are more gently inclined than the gorges that are characteristic of the sandstones at higher elevations around the perimeter of the Sydney Basin.

On the crests and ridges, soils consist of up to 20 cm of loose, coarse quartz sand overlying either bedrock or <30 cm of earthy, yellowish-brown sandy-clay-loam subsoil. Where directly over rock, it forms Lithosols (Rudisols) and where over subsoils it forms Earthy Sands or Yellow Earths (Yellow-Orthic Tenosols). Total soil depth is <50 cm. The boundary between soil materials is usually gradational and texture often increases slowly with depth. On sideslopes and benches the soils are discontinuous, with sandstone outcrop and boulders common. Usually 10-30 cm of loose, coarse quartz sand overlies bedrock forming Lithosols and Siliceous Sands (Rudisols) on the outsides of benches, whilst 5-15 cm of earthy, yellowish-brown sandy-clay-loam subsoil occurs on upper sides of benches. Boundaries between soil materials are either gradual or clear and total soil depth, although variable, is usually <70 cm. In some instances, especially along joint lines, soil depth may exceed 2 m producing Yellow Earths and Yellow Podzolic Soils (Yellow Chromosols) (Atkinson 1992). In all cases, soils are of low fertility. A description of the micro- geomorphic features on benched Hawkesbury Sandstone and soils typical of this site is found in Gould (1998).

A series of sediment traps were installed in the catchment four days after the fire. Five sampling sites were chosen as representative of the landscape elements within the catchment. These consisted of a crest, an upper sandstone bench, a sideslope, a footslope and a small valley swamp (Fig 1). For each site, the landform element, slope, soils and dominant vegetation are listed in Table 1. Soils at each site were described according to Milford et al. (2001), classified according to Stace et al. (1968) and Isbell (1996) and data recorded in the NSW SALIS database.

A runoff plot similar to that described by Riley et al. (1981) was installed at each of the crest, upper bench and footslope sites. These plots had an area of 9 m^{2} and were designed to measure soil loss from a known area (Figs 2a and 3). An additional 17 modified Gerlach sediment traps, constructed with a one metre wide V-shaped inlet facing upslope, were installed at the five sites, to measure the amount of sediment passing a given point on the slope (sediment flux) (Figs 2b and 4). Sediment samples were collected from the plots and traps after each runoff event until day 72, then at monthly intervals for the first year, then irregularly until 1989, by which time only 14 remained intact and able to provide useful data. Samples were oven-dried. Leaves and sticks were separated from the fine sediment and the two parts weighed. A sub-sample of the fine sediment was then fired at 650^{0}C to remove all organic matter present and the percent weight loss

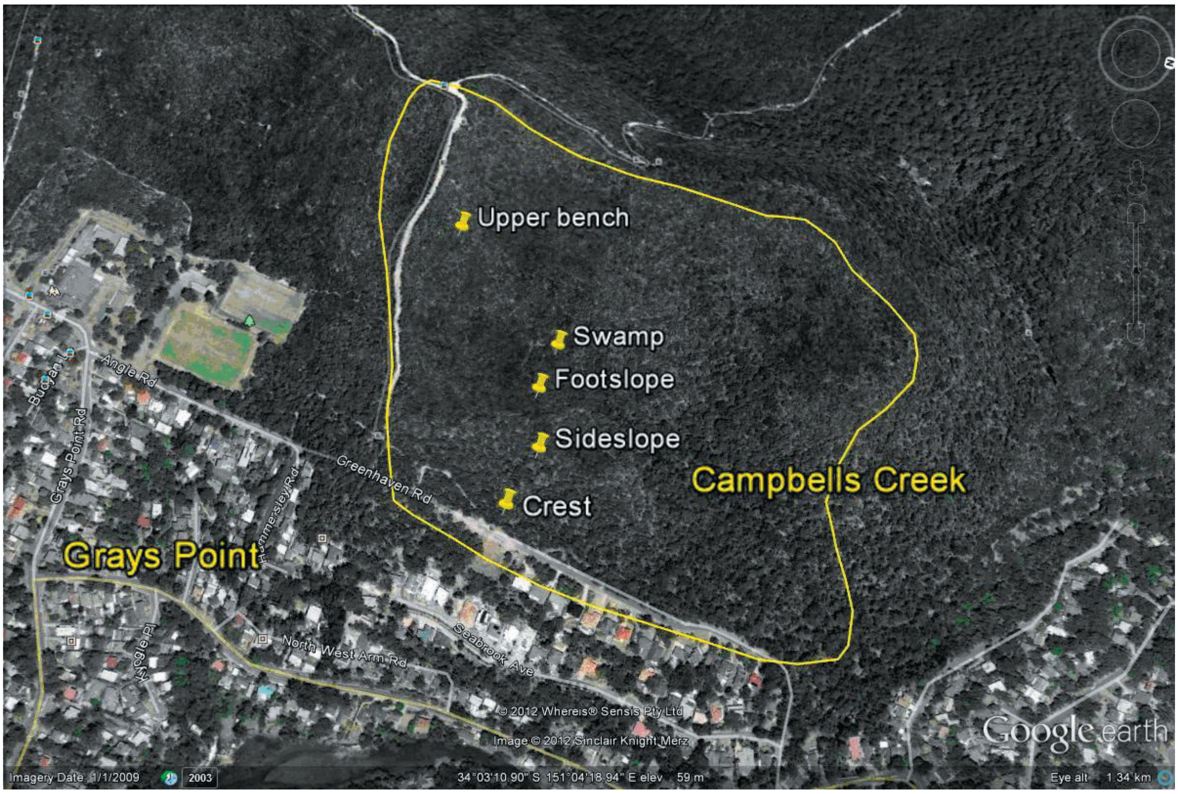


Fig 1. Campbells Creek study area

on ignition (LOI%) calculated. From this figure the mineral soil loss was calculated.

In addition to the sediment sampling, two years after the fire in February 1985, a series of measurements were made of the depth of erosion, or sediment accretion, compared with the still visible burned ground surface. Depth measurements were taken every 0.5 m on a grid 2.5 m wide x 4.5 m long. This was done at nine locations immediately upslope of existing traps and was done to compare results from the two different techniques. Soil loss results using this method assume a soil bulk density of 1.0 (Hazelton and Tille (1990).

The amount of groundcover provided by litter and by vegetation in each of four height strata were recorded at each site on four occasions during the first year using a gridded point count method. This was done to assess the impact of litter and regrowth on erosion rates. Groundcover and regrowth were also recorded photographically on a monthly basis for the first two years then in January 1985, May 1986, February 1987 and finally following another fire in the area in January 1994.

Daily rainfall was measured at Audley visitors centre (BOM station 066001), 1.7 km to the south-west. More frequent readings of high intensity rainfall were taken at Grays Point.

RESULTS

Daily rainfall for 1983 is presented in Figure 5. Soil losses were recorded for each runoff producing event in the first 72 days after the fire. Results for this period are summarized in Table 2. The first runoff event was on 26th January. The bulk of sediment collected after this event was low density organic debris consisting of ash, charcoal and seed. In places, the transported ash debris formed miniature dams several centimetres high (Mitchell and Humphreys 1987) as water washed it down slope before infiltrating. Elsewhere, in depressions, ash debris accumulated to depths of 20 cm. Some sand was also transported, mainly by water concentrated along walking tracks and pre-existing channels and gully lines. Average organic matter content of the first runoff event was 35.2% reflecting the high concentration of ash and fine charcoal. By 21st March this had dropped to 6.3% and it remained at about this figure for the rest of the year (Fig 6). Blong et al. (1982) report a similar fall in charcoal from an initial 25% to < 10% after a few months. Leaf fall from the scorched canopy commenced in the last weeks of January, the resulting litter reaching a maximum cover by the end of February. This was most pronounced on the sideslope where there was a tall canopy. However, by mid-March there was no significant groundcover afforded by live vegetation.

Table 1.Terrain and vegetation at each sampling area

Landform Element	Closed Plot	No. Open Traps	Av. Slope %	Soil Type	Vegetation Structure	Dominant Species
Crest	Plot 1	3	8	Yellow Earth (Yellow-Orthic Tenosol)	Woodland	*Angophora costata* *E. gummifera*
Upper Bench	Plot 2	2	7	Earthy Eand (Leptic Rudisol)	Low-open woodland	*E. haemastoma* *E. gummifera* *Banksia serrata*
Sideslope		4	18	Earthy Eand (Yellow-Orthic Tenosol)	Open forest	*Angophora costata* *E. piperita* *E. gummifera*
Footslope	Plot 3	7	12	Earthy Sand (Yellow-Orthic Tenosol)	Low-open woodland	*Angophora hispida* *E. gummifera* *E. haemastoma*
Swamp		3	2	Siliceous Sand (Stratic Rudisol)	Closed sedgeland	*Cyperaceae*

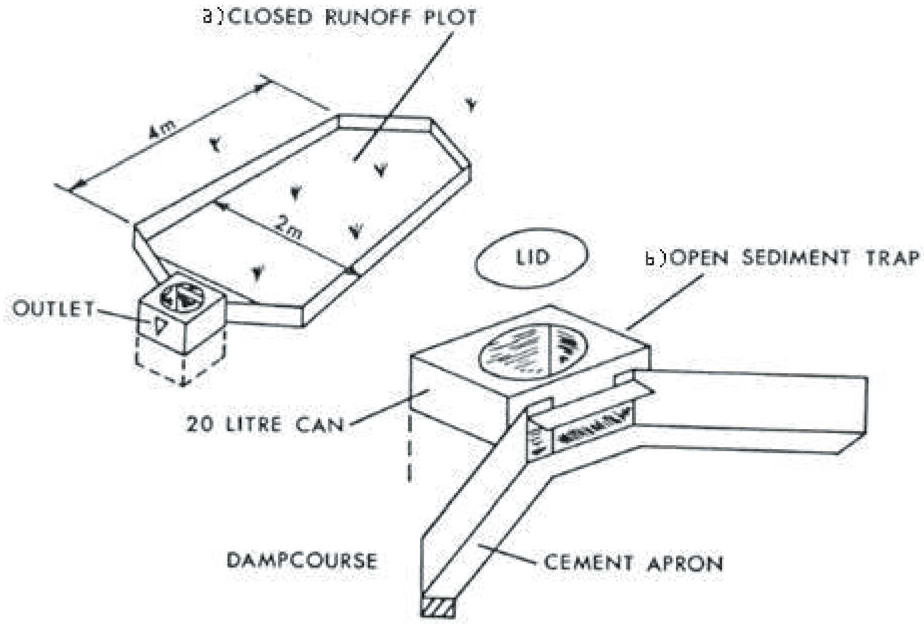


Fig 2. Design of closed plots and open sediment traps

Fig 3. Plot 1, a 9 m² closed plot installed on a crest to measure soil loss in t ha-1

Fig 4. An open sediment trap 1.0 m wide to measure sediment flux

The weather throughout February and early March was hot and dry with no rainfalls exceeding 3.5 mm and no runoff observed. Between 17th-21st March a quarter of Sydney's annual rainfall fell on the catchment, bringing to an end a four year drought. Storm rains on the 17th March the afternoon of 21st March had return frequencies of 10 years (Table 2) (BoM 2011). During the night of 16th-17th March, 120 mm of rain fell in a six hour period. A significant amount of overland flow occurred, with sand as well as ash debris transported by sheet flow. The runoff water was clear, however, indicating that little dispersed clay was being carried. Runoff durations were longer in this event than in the January rains, with greater runoff volumes. Consequently, both ash and sand were eroded from the hillslopes but only the lighter organic debris flowed through the creeks and out of the catchment. On the other hand, sand was generally trapped on the slopes by small debris dams formed by fallen leaves and sticks. Some open traps located in areas of concentrated runoff were filled beyond their 20 litre capacity.

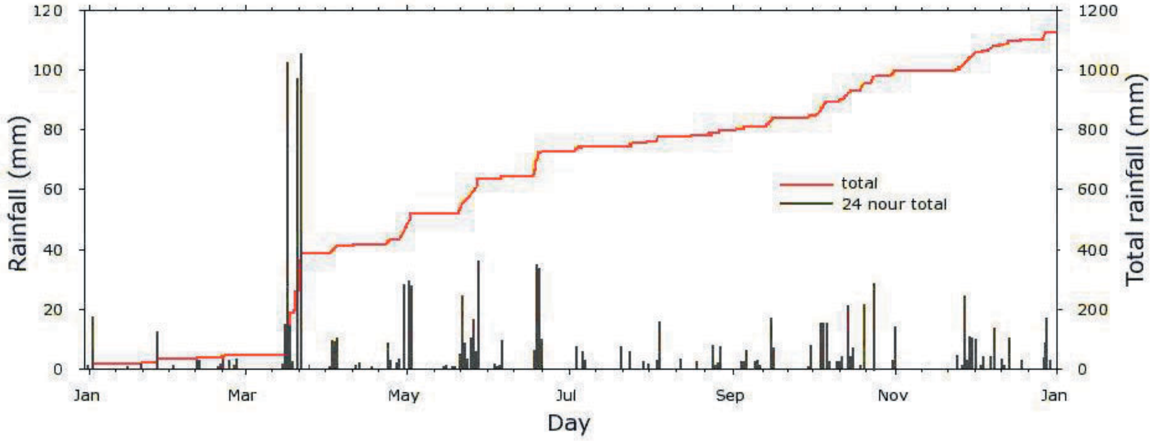


Fig 5. Cumulative daily rainfall at Royal National Park, January 1983 to January 1984

Table 2. Soil loss in the first four runoff events

Date 1983	Days since fire	Rainfall mm	Duration hours	Soil loss range $t\ ha^{-1}$	Soil flux range $kg\ m^{-1}$	% Carbon LOI%
26/1	17	16.5	0.75	0.2 – 1.4	0.01 – 0.63	35.2
17/3	67	120	6.00	2.2 – 7.2	0.2 > 21	22.5
20/3	70	100	27.0	3.8 – 10.3	>20	3.8
21/3	71	100	4.00	13.8 – 32.5	12.5 > 45	6.3

Follow-up rains fell three days later. Over 100 mm of rain was recorded in the 27 hours before noon on 21st March, with a further 100 mm falling during the next four hours. The 150 mm recorded in the 9 hours to 6pm on the 21st was also a 10-20 year return period event. This event resulted in substantial local flooding and infrastructure damage that is described in Atkinson (1984). With the soils already saturated, runoff rates were high and were accompanied by very high levels of soil erosion. Sand clogged all the open traps, not only those located in areas of concentrated flow. Many of the small debris dams formed only days earlier, were breached and large volumes of sand were carried from the slopes into the streams and out of the catchment. By comparison, the closed plots were not filled beyond their capacity. This was because the upslope plot borders prevented normal overland flow from eroding the plot surface as it did on either side. After the rain, the areas surrounding the plots were noticeably more eroded than the protected area within the plot borders. The results presented for the closed plots can therefore be considered underestimates of the true soil loss. Similarly, annual flux figures including this date are minimum figures and cannot be used to compare sites during this event. Consequently comparative sediment flux results in Figure 7 are only for the period 22nd March, 1983 to 10th January, 1984.

Soil loss and sediment flux results for the rest of the year generally reflect the rainfall during each month, with relatively constant flux rates between March and July, dropping during a low rainfall period in August and September and returning to the higher levels from October to January 1984. There is little evidence of diminishing flux rates with increasing groundcover over time (Fig 7). Rather they continued at the a similar rate through to the end of the first year. The average flux rate of the hillslope plots was the equivalent of 9.7 kg m^{-1} $year^{-1}$ for the more typical conditions that existed after March 1983.

Cumulative soil loss for the first 12 months after the fire measured in the three closed plots ranged

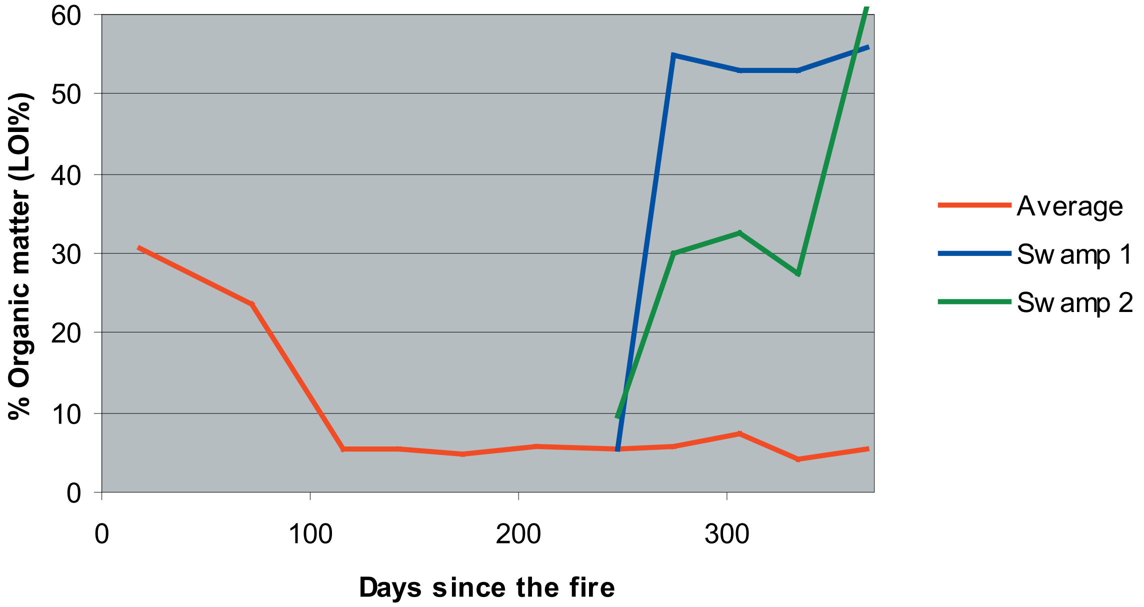


Fig 6. Organic carbon content (LOI%) of sediment vs days since the fire

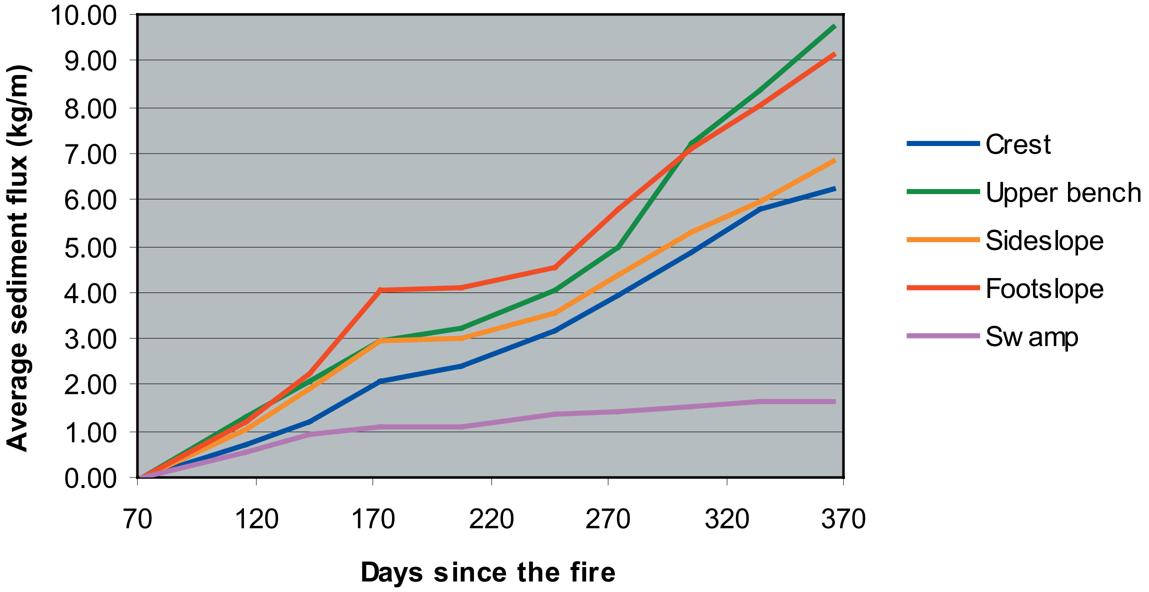


Fig 7. Cumulative sediment flux vs days since the fire, zeroed at day 72, 22nd March 1983

from of 39.6 to 64.2 t ha^{-1}, the bulk of which occurred over the four days in March (Fig 8).

Recovery of native vegetation proceeded at a steady rate during the first year (Figs 9-13). The first plants to recover were those which were able to survive the fire alive and kept on growing by resprouting (Keith 1995). They either resprouted quickly from epicormic buds on stems (e.g. *Eucalyptus, Angophora costata* and *Persoonia levis*) or ground level lignotubers (e.g. *Eucalyptus, Isopogon, Lomatia and Angophora hispida*) or were protected by crowded leaf bases (e.g. *Xanthorrhoea* and *Doryanthes*) or resprouted from rhizomes (e.g. Cyperaceae, *Lomandra, Patersonia, Pteridium* and, Restionaceae). Seedlings began to emerge during autumn and winter and rapid growth of small plants took place through the spring as consistent rains and cooler temperatures maintained high soil moisture levels. This growth continued throughout summer with most small plants surviving the hot summer because of the regular rains. Many plants flowered during spring and summer. Larger trees such as eucalypts and *Angophora costata* shed

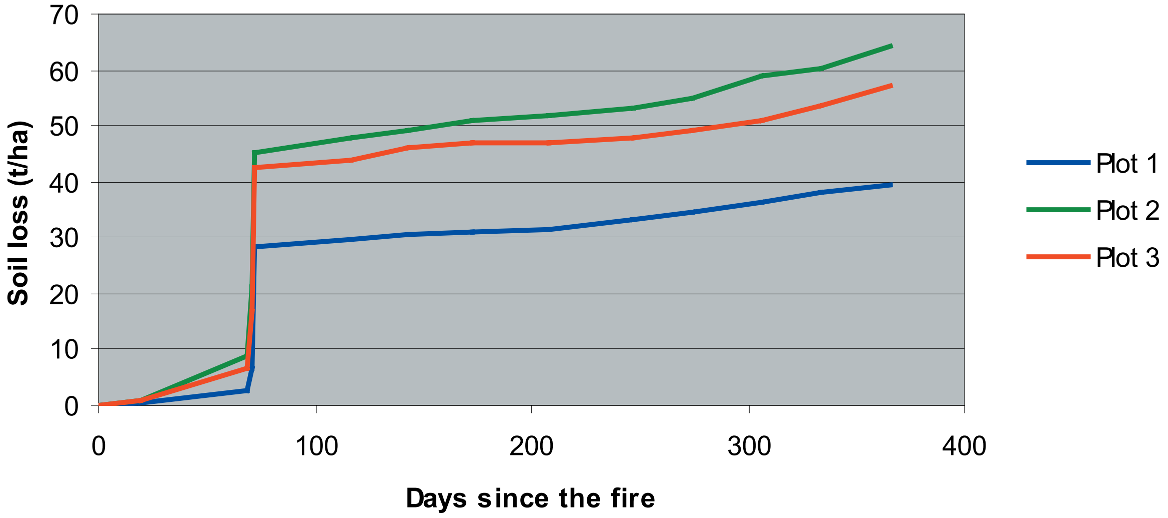


Fig 8. Cumulative soil loss measured in three 9 m2 closed plots vs days since the fire

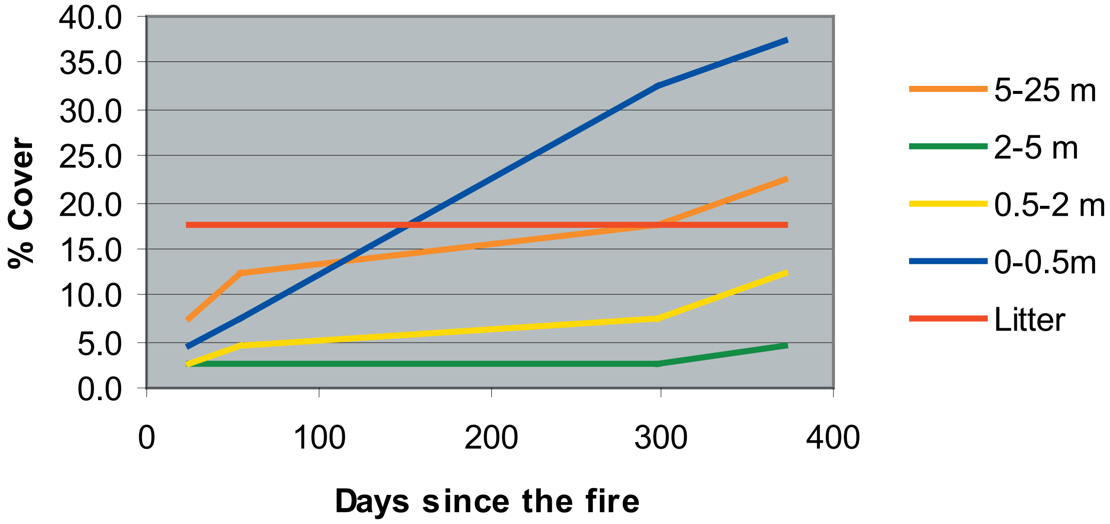


Fig. 9. Recovery of groundcover in 4 height strata and litter for 4 dates following the fire - Crest

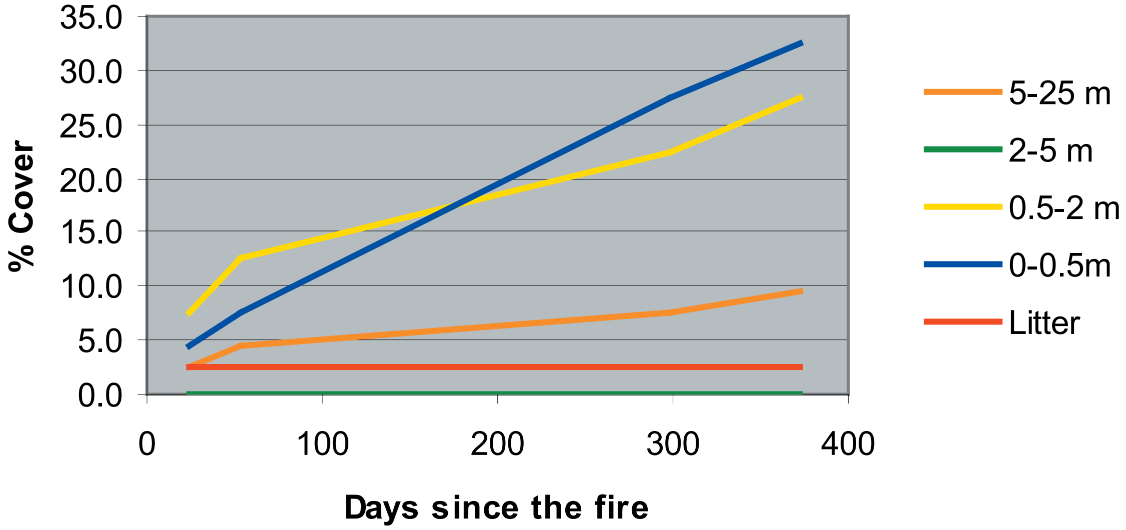


Fig. 10. Recovery of groundcover in 4 height strata and litter for 4 dates following the fire- Bench

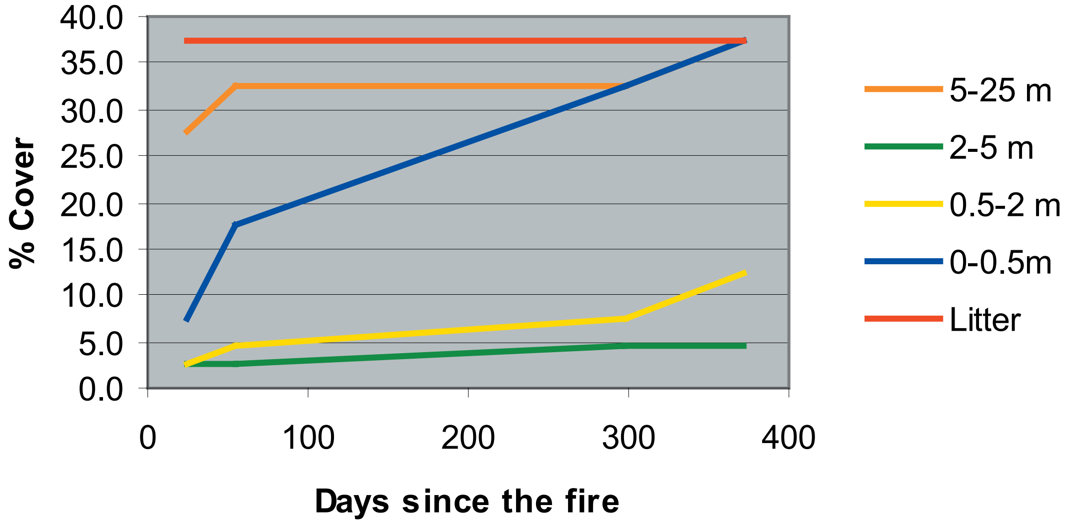


Fig. 11. Recovery of groundcover in 4 height strata and litter for 4 dates following the fire - Sideslope

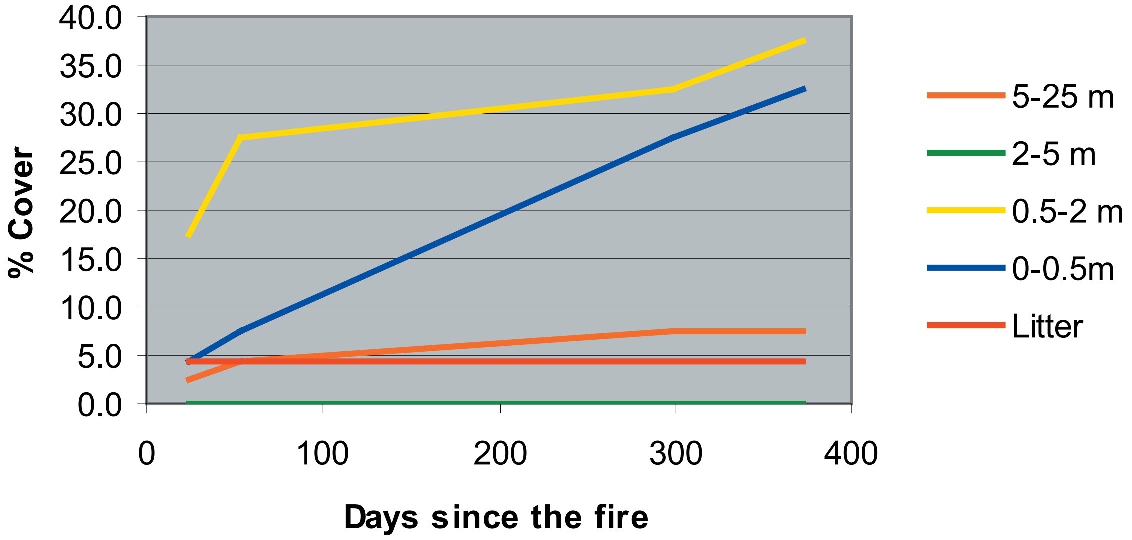
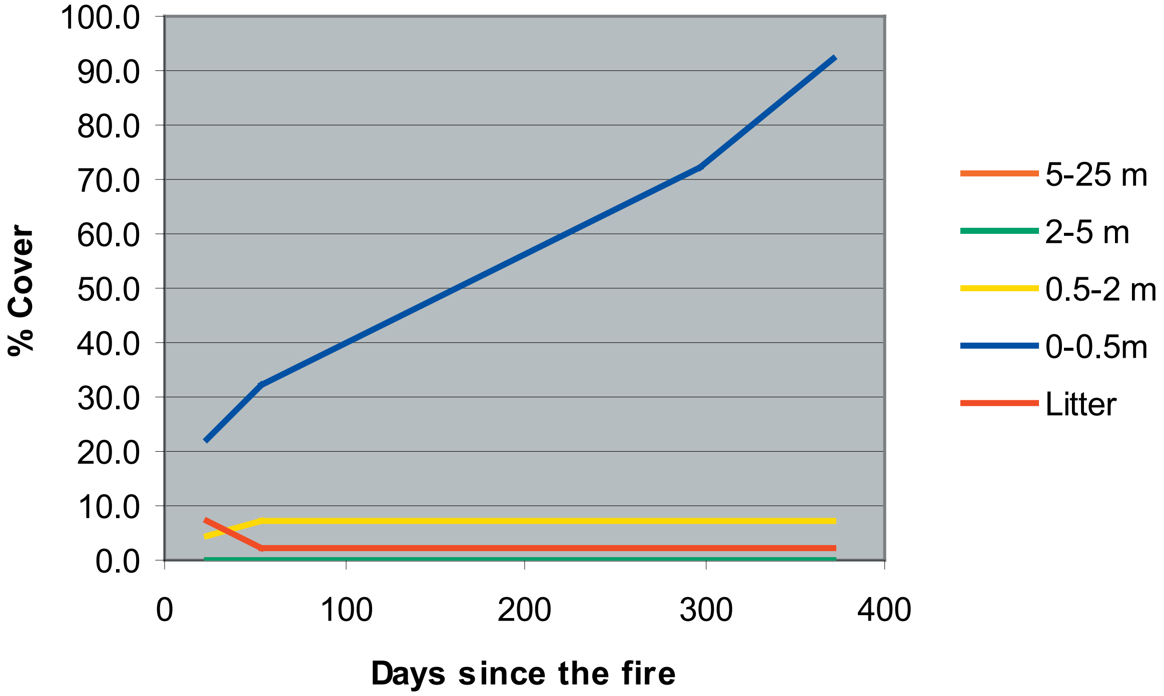


Fig. 12. Recovery of groundcover in 4 height strata and litter for 4 dates following the fire - Footslope



Figs 13. Recovery of groundcover in 4 height strata and litter for 4 dates following the fire - Swamp

bark and sticks in November, substantially increasing litter cover around them. However, since the initial drop of dead leaves in February, very few trees had old leaves, so the leaf litter generally did not increase since that time. Most noticeable growth was in the 0 - 0.5 m stratum, as would be expected, where most sites recorded over 30% cover by the end of the year. The only area where regrowth of vegetation could be seen to influence erosion and sedimentation rates was in the sedge swamp (Fig 7). Here flux rates tapered off to low levels after June, by which time regrowth of the sedges had been sufficient to prevent the sediment which entered the swamp from being transported through it. The corresponding change in sediment composition between sand and organic material is reflected in Figure 6 as the light organic material continued to be transported. Groundcover of sedges had reached 92% by the end of the year. These swamp results would suggest that sediment had ceased discharging from the catchment by June.

On the 9th November 1984, 22 months after the fire, 279 mm of rain was recorded at Audley. This represents a 20-50 year return period event, effectively much larger than that of March 1983. Significantly, during this event there was no flooding or infrastructure damage downstream. This can be accounted for by higher infiltration rates, improved groundcover and increased surface roughness due to vegetation regrowth. Although localised soil loss may have still been significant there was an effective filter in place with thick vegetation in the swamp. There was however, noticeably more erosion observed along walking trails.

Measured changes in the height of the post fire ground surface upslope of nine traps in January 1985 revealed soil loss figures in the same range as was obtained in the closed plots over the first year (Table 3). Individual values near the three closed plots were 14.9 t ha^{-1} for plot 1, 44.4 t ha^{-1} for plot 2 and 52.7 t ha^{-1} for plot 3. This method demonstrated that there was both erosion and sedimentation over short distances with 48% of points eroded, 30% with sediment accumulation and 22% with no change to the net surface height. Discrepancies between the plot results and these ground surface measurements can be partly attributed to the greater exhaustion of sediment supply in the closed plots whereas outside the plots sediment also accumulated in micro-terraces. These measurements also had greater variability demonstrating the effects of local variations in overland flow paths. As an example, measurements near two adjacent traps on the crest that had similar results in the first year had the equivalent of 14.9 t ha^{-1} of soil loss and 15.8 t ha^{-1} of accretion respectively

Table 3. Net soil loss measured by change in ground height at nine locations after two years

Landform element	Location above	Slope %	Soil loss t ha^{-1}
crest	Plot 1	8%	14.9
crest	Trap 4	5%	-15.8
sideslope	Trap 21	12%	36.4
footslope	Plot 3	13%	52.7
footslope	Trap 28	10%	4.9
footslope	Trap 33	13%	11.1
upper bench	Plot 2	6%	44.4
Upper bench	Trap 8	8%	32.7
Average			**22.6**

by the end of the second year indicating local redistribution of hillslope sediments.

Rainfall records for the 11 year period from January 1983 to January 1994 from Audley reveal that a number of high return period rainfall events occurred during this period, at least eight of which exceeded a 1:10 year return period (Table 4) (BoM 2011). Between 1986 and 1989 there were two high return period rainfall events for which soil losses were recorded (Table 5). Whilst the 20-50 year return period event of 9th November 1984 produced noticeable soil erosion, the events of August 1986, April 1988, February 1990, June 1991 and February 1992 passed without visible impact. Rainstorms on 5th and 6th August 1986, 3.5 years after the fire, were a 10 year return period event of similar magnitude to that of March 1983, yet this event yielded soil losses of only 0.25 to 2.19 t ha^{-1} and flux rates which averaged 0.2 kg m^{-1}. The plots were monitored 6 months and 12 months after this storm event by which time soil losses had dropped appreciably (Table 5). Over the following 15 months to January 1989 there was only 0.07 to 1.15 t ha^{-1} recorded despite a 20 year return rainfall event on 30th April 1988. Similarly, there was either no fresh sediment or up to 0.1 kg m^{-1} sediment flux in the open traps. Again the even bigger event of June 1991 passed without impact indicating clearly that the bushland had returned sufficient groundcover to protect the soil from erosion.

DISCUSSION

The soil losses in the year following a bushfire measured in the closed plots in this study of 39.6 to 64.2 t ha^{-1} are higher than the 2.5 to 8 t ha^{-1} recorded in similar terrain by Blong et al. (1982). However, like Dragovich and Morris (2002), their results were obtained during a relatively dry year (60% of average rainfall) and their suggestion of soil losses in excess of 20 t ha^{-1} in an average rainfall year is a realistic estimate for Hawkesbury Sandstone terrain. Even if the more extreme events of March 1983 are removed from the figures presented here, soil losses for the period April 1983 to January 1984 still range from 11.1 to 20.4 t ha^{-1} which is consistent with their prediction.

However sediment flux rates measured in the open plots suggest that the closed plots significantly underestimated the actual erosion taking place on the slope during the high rainfall events in March 1983 because the plot borders were deflecting overland flow. This suggests that the open traps measuring sediment flux, despite the obvious problems in this study of undersized containers and unknown contributing areas, may well provide a more realistic measure of erosion rates than the closed plots. Soil

Table 4. High rainfall events for the period January 1983 to January 1994

Year	Date	Daily rainfall mm#	Return frequency	
1983	17th March	120/6 hours	10yr	
	21st March	150/9 hours	10-20yr	
1984	9th November	279*	20-50yr	
1985	5th December	117*	1-2yr	
1986	5th August	116	1-2yr	10yr
	6th August	142*	2-5yr	
1987	11th August	111	1-2yr	
	25th October	98*	1yr	
1988	30th April	173	20yr	
1990	3rd February	175*	20yr	20yr
	4th February	132	2yr	
1991	11th June	300*	50yr	100yr
	12th June	108	1-2yr	
1992	9th February	107	1-2yr	
	10th February	170	20yr	
#(BoM, 2011)		* monthly record rainfall		

Table 5. Soil loss during the bushland recovery phase

	Plot 1	Plot 2	Plot 3	Average flux
Date	**t ha^{-1}**	**t ha^{-1}**	**t ha^{-1}**	**kg m^{-1}**
8/08/1986	0.54	2.19	0.25	0.20
23/02/1987	0.21	0.94	1.29	0.15
24/09/1987	0.07	1.12	0.16	0.12
1/01/1989	0.07	1.57	0.18	0.19

loss rates remained relatively high 12 months after the fire, notwithstanding good regeneration of native vegetation, but by two years, and again 3.5 years after the fire even major rainfall events of similar magnitude to that of March 1983, produced minimal sheet erosion. However, erosion along bare walking trails was observed to continue throughout the study period.

Erosion rates measured by comparing actual soil surface deflation or accretion with the burned surface after two years indicated similar rates of soil loss to those predicted by Blong et al. (1982) but somewhat less than those recorded in the closed plots in this study, averaging 22.9 t ha^{-1} in two years. This is attributed to small scale erosion and sedimentation on the hillslopes and the possible exhaustion of loose soil within the closed plots.

Between four and five years after the fire the soil loss rate had fallen to an average of 0.62 t ha^{-1} and sediment flux to 0.15 kg m^{-1} approximating 1% of the peak soil loss and 0.3% of the peak sediment flux observed in the first year.

The results of this study highlight the importance of the more intense rainfall events as erosive agents, particularly in the period immediately after the fire and that significant erosion should be expected in such circumstances. This is consistent with observations of numerous authors including Good (1973), Booker et al. (1993), Leitch et al. (1983), Prosser and Williams (1998) and Wallbrink et al. (2004). The frequency of these high rainfall events during the 11 year study period was certainly much higher than their predicted return frequency, there being eight such events in excess of 100 mm per day. This is a much higher threshold than the greater-than-one-year recurrence interval that Prosser and Williams (1998) suggest is required to generate substantial runoff and sediment yield. The observed frequency of these high magnitude events would suggest that the chances of a significant erosive rainfall event occurring before groundcover is well established after a fire in this terrain is quite high, contrary to the predictions of Prosser and Williams (1998) that the convergence of high intensity fire and an intense storm event would be rare.

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