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The effect of wildfire on runoff and erosion in native *Eucalyptus* forest

Ian P. Prosser[1*] and Lisa Williams[2]

[1]*Cooperative Research Centre for Catchment Hydrology, CSIRO Division of Water Resources, GPO Box 1666, Canberra, ACT 2601, Australia*

[2]*School of Geography, University of New South Wales, Sydney, NSW 2052, Australia*

Abstract:

Wildfires raise concerns over the risk of accelerated erosion as a result of increased overland flow and decreased protection of the soil by litter and ground vegetation cover. We investigated these issues following the 1994 fires that burnt large areas of native *Eucalyptus* forest surrounding Sydney, Australia. A review of previous studies identifies the fire and rainfall conditions that are likely to lead to increased runoff and accelerated erosion. We then compare runoff and erosion between burnt and unburnt sites for 10 months after the 1994 fires.

At the scale of hillslope plots, the 1994 fire increased runoff by enhancing soil hydrophobicity, and greatly increased sediment transport, mainly through the reduced ground cover, which lowered substantially the threshold for initial sediment movement. However, both runoff and sediment transport were very localized, resulting in little runoff or sediment yield after the fire at the hillslope catchment scale. We identify that after moderately intense fires, rainfall events of greater than one year recurrence interval are required to generate substantial runoff and sediment yield. Such events did not occur during the monitoring period. Past work shows that mild burns have little effect on erosion, and it is only after the most extreme fires that erosion is produced from small, frequent storms. © 1998 John Wiley & Sons, Ltd.

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KEY WORDS fire; overland flow; surface wash erosion; *Eucalyptus* forest

INTRODUCTION

A series of wildfires burnt 4000 km^2 of *Eucalyptus* forest along the coastal ranges of New South Wales over two weeks in January 1994. The fires burnt widespread areas of National Park and reserve surrounding the Sydney metropolitan area, prompting media attention to the subsequent effects on these largely natural landscapes. The major concerns were over ecological effects but the media also alerted the community to the risk of greatly accelerated erosion and the impact this could have on nutrient levels and sediment loads in streams. The then New South Wales Department of Conservation and Land Management was put under pressure to prevent erosion using broad-acre measures such as hydromulching, but chose to direct its resources mostly to fire-trail and fire-break repair. None the less, there is an increasing trend towards costly intervention aimed at preventing post-fire erosion in many environments (Booker *et al.*, 1993).

Public concern over the Sydney fires raises the question of how real is the risk of greatly accelerated erosion after wildfire. The scientific literature records a diverse range of responses of runoff and erosion to fire. There are, however, broad patterns of response which reflect fire and rainfall intensity, and the predominant hydrological and erosion processes.

To help improve our understanding of erosion following fire we outline a conceptual framework of how landscapes respond to fire, and assess this against previous studies of post-fire runoff and erosion, focusing

* Correspondence to: Ian P. Prosser.

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primarily on native *Eucalyptus* forests. We add to these data the results of our own monitoring following the 1994 Sydney fires. Our experimental approach was to compare processes between a burnt and an unburnt hillslope catchment. This enabled us to separate the effect of increased runoff from that of decreased resistance to erosion, and to improve our understanding of runoff and erosion processes in *Eucalyptus* forests.

EROSIONAL RESPONSE TO FIRE

Conceptual framework

Fire is a natural disturbance to landscapes that affects erosion indirectly by reducing the resistance of the landscape to erosion and, in places, by increasing the energy of runoff. It is the magnitude of changes to attributes such as litter and ground vegetation cover, soil structure, soil hydrophobicity and infiltration rate that control erosion following a fire. Over time these attributes relax back to pre-fire levels (Brunsden and Thornes, 1979) so that resistance to erosion gradually increases and the energy of runoff gradually returns to normal. Consequently, there is a limited window of time during which there is potential for erosion to be accelerated (Figure 1). This window of disturbance may range from just one month to several years (e.g. Brown, 1972; Prosser, 1990). In the hypothetical example shown in Figure 1, relaxation to pre-fire conditions follows an exponential function, and the frequency and magnitude of runoff are increased by the fire, but runoff exceeds resistance to erosion on only three occasions. In this paper we concentrate on the processes of surface wash erosion following fire, although the same concepts could be applied to processes such as channel erosion or debris flows, which are important in other landscapes (e.g. Laird and Harvey, 1986; Florsheim *et al.*, 1991; Meyer *et al.*, 1992).

In environments where overland flow is relatively frequent, the effect of fire on surface wash erosion depends on the timing of runoff events and their magnitude, which themselves may be influenced by fire. Storms immediately following the fire are most important since these have the greatest potential for erosion, because of the greatly reduced resistance to erosion (Figure 1). Later events may have a lesser effect on erosion, not only because of partial recovery of the landscape, but also because much of the sediment available for transport may have been removed in earlier events (Collins and Dunne, 1986). If no events exceed the resistance of the landscape to erosion during the recovery period then there will be minimal impact from the fire.

One of the difficulties of using the framework shown in Figure 1 is that we cannot measure resistance to erosion directly, we can only infer it from the erosional response to runoff events, or use surrogate measures such as percentage ground cover, the shear strength of soil or the amount of available sediment. The inferred

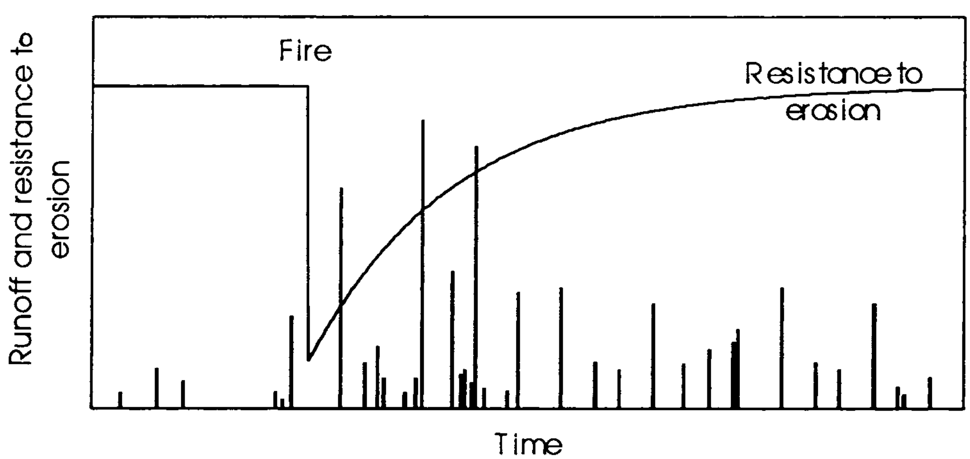

Figure 1. Hypothetical effect of fire on runoff and resistance to erosion. Resistance to erosion is measured as the event size required to generate sediment yield

resistance to erosion may differ between plot and catchment scales if sediment is merely redistributed in parts of the landscape, with no net export from the catchment. Thus, erosion following fire is dependent on the magnitude of the disturbance, the relaxation time of the disturbance, the magnitude of runoff events and the scale of measurement. The concepts of Figure 1 also apply to other forms of disturbance, such as timber logging, and reference is often made to natural disturbances such as wildfire when assessing the effect of logging on a landscape (e.g. Burgess *et al.*, 1981; Megahan, 1983).

Fire severity is often measured in terms of the volume of fuel burnt, or the maximum soil temperatures attained (Walker *et al.*, 1986). For wildfires these properties are rarely measured, and for the purposes of predicting erosion the severity of a fire is best measured by its effect on soils and vegetation. Mild fires burn only the understorey vegetation, which re-sprouts quickly from unburnt roots. There is little effect on soil structure or organic matter, but soil hydrophobicity is still possible. Moderately intense fires burn all levels of vegetation, and soil hydrophobicity is likely to be widespread. The soil surface is left bare and becomes more prone to erosion through burning of organic matter that provides soil cohesion, leaving a loose surface of ash and dry soil (Giovannini and Lucchesi, 1983). Shrubs may be killed by these fires, but grass and *Eucalyptus* trees usually recover. In the most extreme fires, some trees and ground vegetation are killed, and the soil temperature can be hot enough to break soil aggregates into fine powder, in addition to removing organic matter and creating strong soil hydrophobicity. It can take several years for soil and vegetation to recover from moderately intense and extreme fires.

Changes to runoff

The main effect of fire on runoff is to increase the soil hydrophobicity that is associated with organic matter (Krammes and DeBano, 1965; Bond, 1968; Bisdom *et al.*, 1993). Fire vaporizes organic compounds, which then condense, coating soil particles in a hydrophobic film (DeBano *et al.*, 1970; DeBano, 1981). Sandy soils or loose crumb-structured soils are most prone to hydrophobicity (McGhie and Posner, 1980; DeBano, 1981).

The significance of fire-induced hydrophobicity for increasing runoff has been questioned in recent years. Many soils are naturally hydrophobic, particularly during summer in semi-arid and sub-humid environments (DeBano, 1981; Barrett and Slaymaker, 1989; Burch *et al.*, 1989), and in some cases fire does not increase hydrophobicity (Doerr *et al.*, 1996). Many forest soils are also highly permeable, with preferential flow along plant roots and macropores. Consequently, locally generated runoff may infiltrate further downslope (Burch *et al.*, 1989; Imeson *et al.*, 1992; Booker *et al.*, 1993), thus explaining why increases in runoff observed at the plot scale are not always reflected in catchment-scale runoff (Kutiel and Inbar, 1993; Scott, 1993). For these reasons it is instructive to compare the hydrology of burnt and unburnt parts of the landscape when invoking the effect of hydrophobicity, and to compare responses at plot and catchment scales.

In some circumstances soil permeability may be so high that there is little overland flow even under hydrophobic conditions. These are situations where rapid throughflow is the predominant process. Under such conditions, the soil surface may be bare and very erodible but the lack of overland flow means there is little risk of surface wash erosion (Booker *et al.*, 1993). This applies to the wetter *Eucalyptus* forests where moderately intense fires result in little erosion (e.g. Humphreys and Craig, 1981; Vertessy, 1984).

Hydrophobicity is most likely to increase catchment runoff in areas dominated by Hortonian overland flow, and after intense fires. Brown (1972) and Mackay and Cornish (1982), for example, recorded greater runoff and flashier stream hydrographs, which persisted for at least two years, following extreme fires, whereas a mild burn monitored by Prosser (1990) produced increased runoff in only the first event after the fire.

Changes to surface wash erosion

Increased runoff alone can result in greater erosion following a fire but this is enhanced by the reduced vegetation and litter cover and low cohesion of ash and desiccated soil. Reduced vegetation cover leads to greater splash erosion, which is also enhanced by soil hydrophobicity (Terry and Shakesby, 1993), and is the dominant process of sediment generation (Ellison, 1944; Moss *et al.*, 1979). The removal of ground cover also leads to faster flows which have a higher sediment transport capacity (e.g. Thornes, 1980). Thus, hillslope sediment yields after fires can be orders of magnitude greater than under undisturbed conditions (Brown, 1972; Diaz-Fierros *et al.*, 1987; Scott and Van Wyk, 1990). Such large effects are, however, highly dependent on the intensity of storms following the fire. This is illustrated by the difference in soil loss from 8–9 m^2 closed plots installed after intense fires in the Sydney area in 1979 (Blong *et al.*, 1982) and 1983 (Atkinson, 1984). The maximum sediment, yield recorded by Bong *et al.* (1982) was 0·5–2·5 kg of sediment from a short storm with a 30 min rainfall intensity of 41 mm/h. This event had a recurrence interval of <1 year, but it was the most intense event in the year following the fire. In contrast, the 1983 fires were followed within three months of the fire by two 10-year recurrence interval storms. These yielded 12–29 kg of sediment from each plot, and more severe erosion was observed outside the enclosed plots (Atkinson, 1984).

After the most extreme fires, surface damage is so great that even small events can lead to massive rates of soil erosion. Brown (1972) recorded sediment yields of 2500 t/km^2 in a 48 km^2 catchment from just 16 mm of rainfall over two hours, in an area where runoff was greatly enhanced by an extreme fire. Similarly, Leitch *et al.* (1983) measured soil erosion of 1900–11 000 t/km^2 from hillslopes after an extremely intense fire in 1983, where widespread overland flow was produced from a daily rainfall of only 17 mm.

While the first intense storms usually produce the greatest soil loss, accelerated erosion has been observed to continue for periods of at least six months (Burgess *et al.*, 1981) to more than one year after fire (Brown, 1972; Prosser, 1990). Vegetation cover can take four to five years to recover from fire (Brown, 1972; Good, 1973) and litter levels increase consistently for seven years after fire (Fox *et al.*, 1979) indicating the maximum period for recovery of resistance to erosion. What is not known, however, is how much vegetation or litter cover is required to prevent accelerated erosion effectively, so recovery of resistance to erosion may be considerably shorter than that of vegetation.

Mild fires produce little accelerated erosion. Mildly burnt open plots installed after a wildfire in 1987 produced significant sediment in only the first event following the fire, and sediment yield was an order of magnitude lower than on an intensely burnt slope (Prosser, 1990). The mild burn had little effect on soil organic matter and the grass recovered within three months of the fire. Similarly, control burns used in forestry management have little effect on runoff and erosion because of the low level of disturbance and the rapid recovery of ground cover, although there may be cumulative effects from repeated burning (Biswell and Schultz, 1957; DeBano 1981; Richter *et al.*, 1982).

Most studies that monitor erosion following a fire are unable to isolate the influence of reduced resistance to erosion from the influence of increased runoff. This can be overcome by comparing erosion between burnt and unburnt plots under a range of runoff conditions.

Overall, past studies show consistent patterns in the magnitude of disturbance and the time of recovery. The most extreme fires disturb the soil surface and increase runoff to such an extent that rainfall of only 10–20 mm can result in widespread runoff and massive soil erosion. Subsequent soil loss is probably then limited by declining sediment availability but runoff and resistance to erosion do not return to unburnt levels for at least one to two years. Moderately intense fires may also increase overland flow but intense rainfall is required for substantial erosion. Runoff and resistance to erosion recover within three months of mild fires, greatly reducing the probability of accelerated erosion beyond the first event after a fire. We used the 1994 Sydney fires to resolve, in more detail, the recovery time and the size of storm that leads to accelerated erosion following a moderately intense fire.

STUDY SITE

We monitored one burnt and one unburnt hillslope catchment for 10 months immediately after the 1994 Sydney fires. The catchments are in native *Eucalyptus* forest on the south side of the Georges River, near Sandy Point, 25 km south-west of Sydney GPO. We chose catchments that were as similar to each other as possible, although small differences were inevitable. The terrain is typical of the large areas of National Park and reserve that surround Sydney. These reserves are found on Triassic Hawkesbury Sandstone, a formation of terrigenous, horizontally bedded, quartz sandstone that is very resistant to weathering. This results in frequent rock outcrops on the steeper slopes which have a characteristic bench form of low gradient above the outcrop, a 1–5 m high and 5–30 m long vertical cliff and a steep footslope with frequent boulders.

The sandstone is composed of >90% quartz grains of medium to coarse sand, resulting in poorly developed sandy soils of 0–1 m depth. The top 5 cm of soil has a dark organic staining, above a granular, uniform, loamy sand (Northcote, 1979) with frequent stones. Deeper profiles have an incipient B horizon of sandy loam texture. The hillslope catchments support an open *Eucalyptus* forest, below which is an open shrub understorey of 1–2 m height, and a complete ground cover of grasses and litter. The area has a humid temperate climate with a mean annual rainfall of 850 mm spread relatively evenly over the year. Summer is the wettest season with 250 mm of rainfall on average for December–February, and winter is the driest season with 165 mm of rain for June–August.

The burnt catchment (33°59′S, 150°00′E) has an area of 5·4 ha and a relief of 30 m, while the unburnt catchment, 2·5 km to the north-west (33°58′S, 149°59′E), has an area of 3·4 ha and a lower relief of 20 m, with less frequent rock outcrops. Fire moved through the burnt catchment on 9 January 1994, destroying all ground cover and some shrubs and small trees. The forest canopy was singed but remained intact, with the dead leaves falling to the ground over subsequent weeks. Plant roots and large logs remained after the fire and grasses re-sprouted from the root stocks. Radionuclide analyses showed that the fire volatilized all ^{7}Be in the soil, but ^{137}Cs remained (Elliot, 1994, personal communication), suggesting that the soil temperature was between 200 and 400°C during the fire. The fire was of moderate intensity, similar to those monitored by Blong *et al.* (1982) and Atkinson (1984), but less intense than the extreme burns recorded by Brown (1972), Good (1973) and Leitch *et al.* (1983). The ^{137}Cs inventory was similar for the burnt and unburnt catchments, indicating comparable erosion rates over the last 40 years. Prior to 1994, both catchments were burnt by a controlled fire in 1989.

METHODS

The same measurements were applied to the burnt and unburnt catchments. All equipment was installed in the catchments within three days of the fire, and before the first rainfall. Catchment runoff was measured through a USDA HS flume (United States Department of Agriculture, 1962) using a Stevens-type F chart recorder attached to a float gauge. Unfortunately, this equipment was stolen from the unburnt catchment two weeks after being installed and could not be replaced, so catchment-scale data are only available from the burnt site. A tipping bucket and a storage rain gauge were installed in the burnt catchment. A second storage gauge at the unburnt site was stolen.

Four, 2 m wide runoff troughs were constructed in each catchment, at arbitrary locations down each hillslope. The troughs were lined with cement, forming a smooth contact with the soil surface, and were covered to protect them from direct rainfall. Water and sediment were collected from the troughs in two, connected, 20 litre drums. The contributing plot area to each trough was poorly defined, as no walls were installed. However, unlike closed plots, the design does not limit the area of runoff generation. Gradients on the plots varied from 4 to 11°, with most of the gentler plots occurring at the unburnt site.

The plots were visited after each rainfall event. The volume of stored runoff was measured in the field and it was then passed through a 63 μm sieve. The retained sediment was oven-dried and weighed. The mass of finer sediment was estimated from an oven-dried 250 ml subsample of runoff. Over 90% of the sediment was coarser than 63 μm as a result of the sandy soils. The percentage of projected ground cover provided by vegetation, leaf litter and ash was assessed visually after each runoff event.

Sediment transport through the catchment outlet was not measured directly. However, runoff from the burnt catchment passes over a 10 m wide, level track before entering the Georges River. Given the low runoff recorded after the fire, at least some proportion of sand transported by the flow would have been deposited on this track, and such observations were used to determine if any sand had been exported during each event.

Water drop penetration time was used to indicate the presence of hydrophobicity near the runoff plots, following the method of Mallik and Rahman (1985). Two surface soil samples were collected adjacent to each plot, at monthly intervals for five months after the fire. The soil was air-dried and passed through a 2 mm sieve to remove coarse litter and gravel, before placing it in a tin and compacting it gently to provide a flat surface. Five, 60 mg water drops were placed on the surface of each sample and the time for complete drop penetration was recorded, up to a maximum time of one hour. Hydrophobicity may develop after fire on either the soil surface (Dekker and Ritsema, 1994; Doerr *et al.*, 1996) or at a few centimetres depth (DeBano, 1981). We sampled near the soil surface because we were interested in processes that generated overland flow from small rainfall events.

RESULTS

Rainfall and surface recovery

The 10 months following the fire were unusually dry with 363 mm of rain, compared with an average of 709 mm (Table I). January and July–October were particularly dry, and March and April were the only months that received greater than average rainfall, and received the largest storms (Figure 2a).

The ground was completely covered after the fire in 1 cm deep ash and dry, loose soil. The first change to the surface was reworking of the soil by ants, which, in the two weeks following the fire, built 20–30 cm diameter mounds of 5–10 cm height covering approximately 5% of the soil surface. Early protection of the soil was provided by leaves blown from the trees, reaching a maximum 60% cover one month after the fire (Figure 2e). Vegetation regrowth provided little effective ground cover until the wetter months of March and April, and much of the ash cover was not removed until that time. Ground vegetation cover had still not fully recovered two years after the fire.

Runoff and hydrophobicity

Runoff was recorded in the hillslope troughs on 16 occasions, identified as events 1–16 (Figure 2a, b). More frequent visits to the site in the early months showed that small rainfall events, generally less than 5 mm in total, produced no runoff. Consequently, we are confident that each measurement of runoff was associated with the single larger event immediately preceding collection, as labelled in Figure 2a.

Runoff was highly variable between plots (Table II), but using an analysis of variance, the mean runoff from plots at the burnt site was significantly higher than at the unburnt site (probability, $p = 0{\cdot}005$). At the level of individual events, a Mann–Whitney U-test found that only events 1, 6, 10 and 16 showed significant differences in plot runoff between sites ($p < 0{\cdot}05$), indicating that differences were more pronounced for smaller rainfall events.

Table I. Comparison of average monthly rainfall with 1994 rainfall for 10 months after the fire

Month	Average rainfall (mm)	1994 rainfall (mm)
January	102	13
February	86	40
March	110	113
April	72	88
May	62	17
June	79	40
July	33	7
August	53	10
September	44	8
October	68	27
Total:	709	363

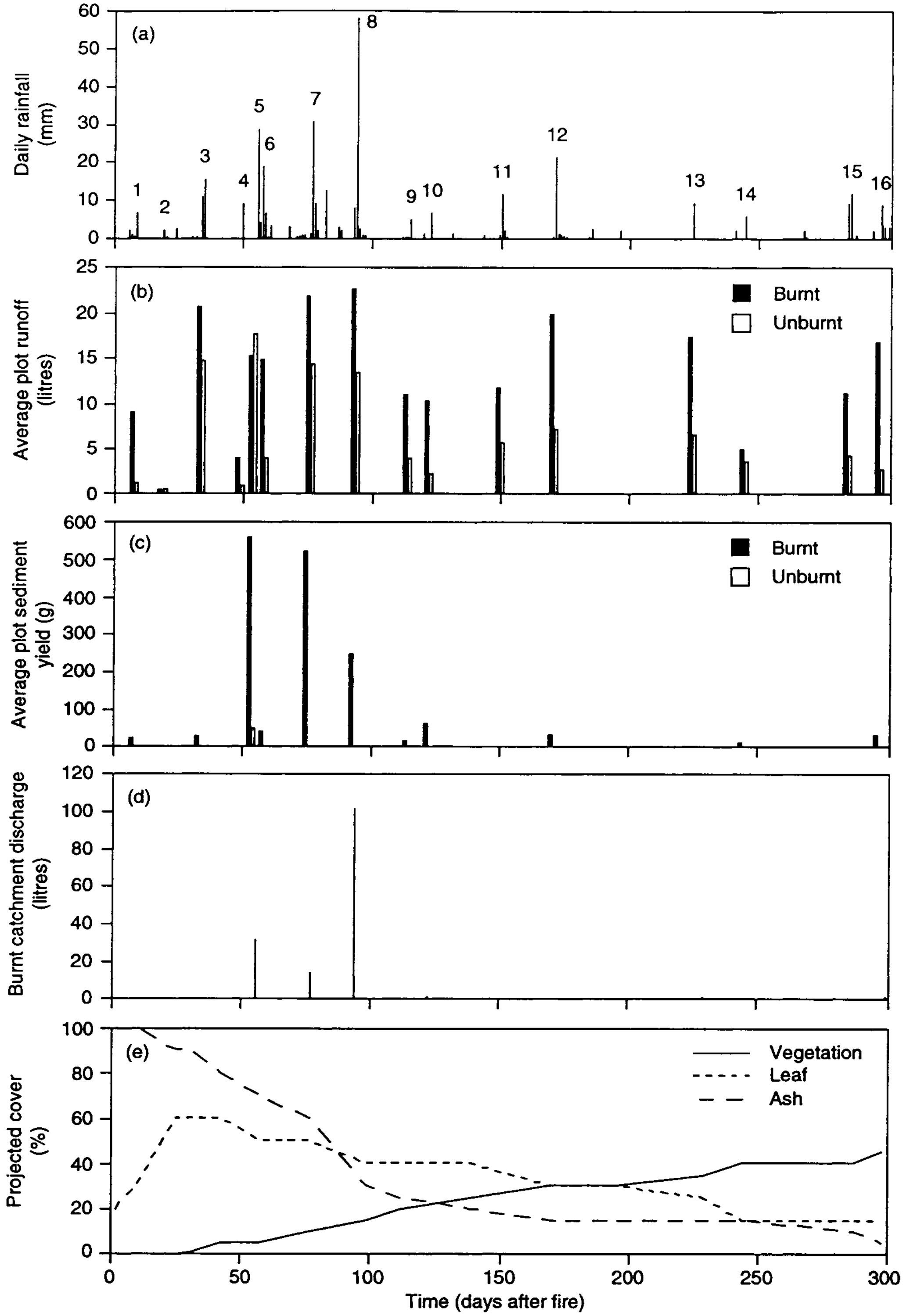

Figure 2. (a) Daily rainfall and event no.; (b) plot runoff; (c) plot sediment yield; (d) burnt catchment runoff; and (e) surface cover at the burnt catchment, following the 1994 Sydney fires

Table II. Plot runoff, sediment yield and water drop penetration time

Event	Plot no.	Burnt site runoff (litres)	Unburnt site runoff (litres)	Burnt site sediment yield (g)	Unburnt site sediment yield (g)	Burnt site water drop penetration time (s)	Unburnt site water drop penetration time (s)
1	1	5	1	4	0	146–1535	19–56
	2	15	1	6	0	48–3600	295–1427
	3	13	0	67	0	67–407	13–35
	4	4	2	7	0	6–135	23–50
2	1	0	0	0	0		
	2	0	0	0	0		
	3	0	0	0	0		
	4	1	0	0	0		
3	1	—	—	—	—	93–299	1–75
	2	—	—	—	—	121–724	4–23
	3	15	2	16	0	141–3600	1–4
	4	27	28	33	0	1–12	1–5
4	1	0	1	0	0		
	2	0	1	0	0		
	3	4	0	5	0		
	4	11	2	3	0		
5	1	4	16	124	0		
	2	18	16	113	45		
	3	19	17	495	0		
	4	22	22	1500	42		
6	1	9	4	9	0	1–1180	2–890
	2	19	2	17	0	30–3600	2–6
	3	16	4	114	0	742–3600	12–60
	4	16	6	15	0	2–73	0–82
7	1	16	8	285	0		
	2	18	12	161	0		
	3	26	10	1200	0		
	4	29	28	447	0		
8	1	21	1	0	0	3–3600	4–90
	2	18	17	38	0	3–29–80	1–18
	3	26	19	722	0	1800–3600	0–3
	4	27	18	234	0	1–4	0–1
9	1	2	4	0	0		
	2	7	3	19	0		
	3	5	3	0	0		
	4	31	7	32	0		
10	1	3	2	6	0	71–3600	5–17
	2	9	2	165	0	35–3600	1–263
	3	13	2	54	0	1500–3600	42–3600
	4	17	5	16	0	2–4	1–11
11	1	3	4	0	0		
	2	1	4	0	0		
	3	15	2	0	0		
	4	29	13	0	0		

Table continued on next page

Table II. Continued

Event	Plot no.	Burnt site runoff (litres)	Unburnt site runoff (litres)	Burnt site sediment yield (g)	Unburnt site sediment yield (g)	Burnt site water drop penetration time (s)	Unburnt site water drop penetration time (s)
12	1	8	8	0	0		
	2	18	0	5	0		
	3	27	4	99	0		
	4	26	18	15	0		
13	1	6	4	0	0		
	2	18	4	0	0		
	3	18	1	0	0		
	4	29	18	0	0		
14	1	1	2	0	0		
	2	4	1	11	0		
	3	5	1	26	0		
	4	11	11	11	0		
15	1	4	2	0	0		
	2	17	1	0	0		
	3	18	1	0	0		
	4	6	15	0	0		
16	1	6	2	0	0		
	2	18	1	27	0		
	3	18	1	75	0		
	4	25	8	22	0		

Runoff was recorded at both sites from surprisingly small rainfall events. For example, in event 14, 8 mm of rain at a maximum 30 min intensity of 7 mm/h produced runoff on all plots. When runoff is graphed as a function of event rainfall, a simple proportional relationship is observed for seven of the plots, with some scatter, and this relationship is maintained even for small rainfall events (Figure 3). The constant of proportionality varies between plots, and is generally higher on the burnt plots, consistent with the overall higher plot runoff at these sites. Linear regression for each data set showed that there was no statistically significant threshold rainfall required to generate runoff on seven of the plots.

Runoff through the outlet of the burnt catchment follows quite a different pattern to the plot results. Catchment runoff of greater than one litre was recorded on only three occasions, and on two of these occasions was less than the total runoff collected in the four 2 m wide troughs (Figure 2d). Only the largest rainfall event, of 68 mm in 24 h, produced substantial runoff. Both the 24 h and 30 min intensities of this event have a recurrence interval of slightly less than one year. We are confident that all catchment runoff was recorded. The flume was concreted on to unweathered rock and the surface of the flume showed no evidence of water flow in the other events.

The measured water drop penetration times record hydrophobic conditions at both sites during the five months of measurement (Table II). Significantly longer water drop penetration times were recorded at the burnt site (analysis of variance, $p < 0{\cdot}01$), consistent with the greater plot runoff at that site. The results were highly variable, both within and between plots, suggesting that hydrophobicity was patchy, with less consistent hydrophobicity at the unburnt site.

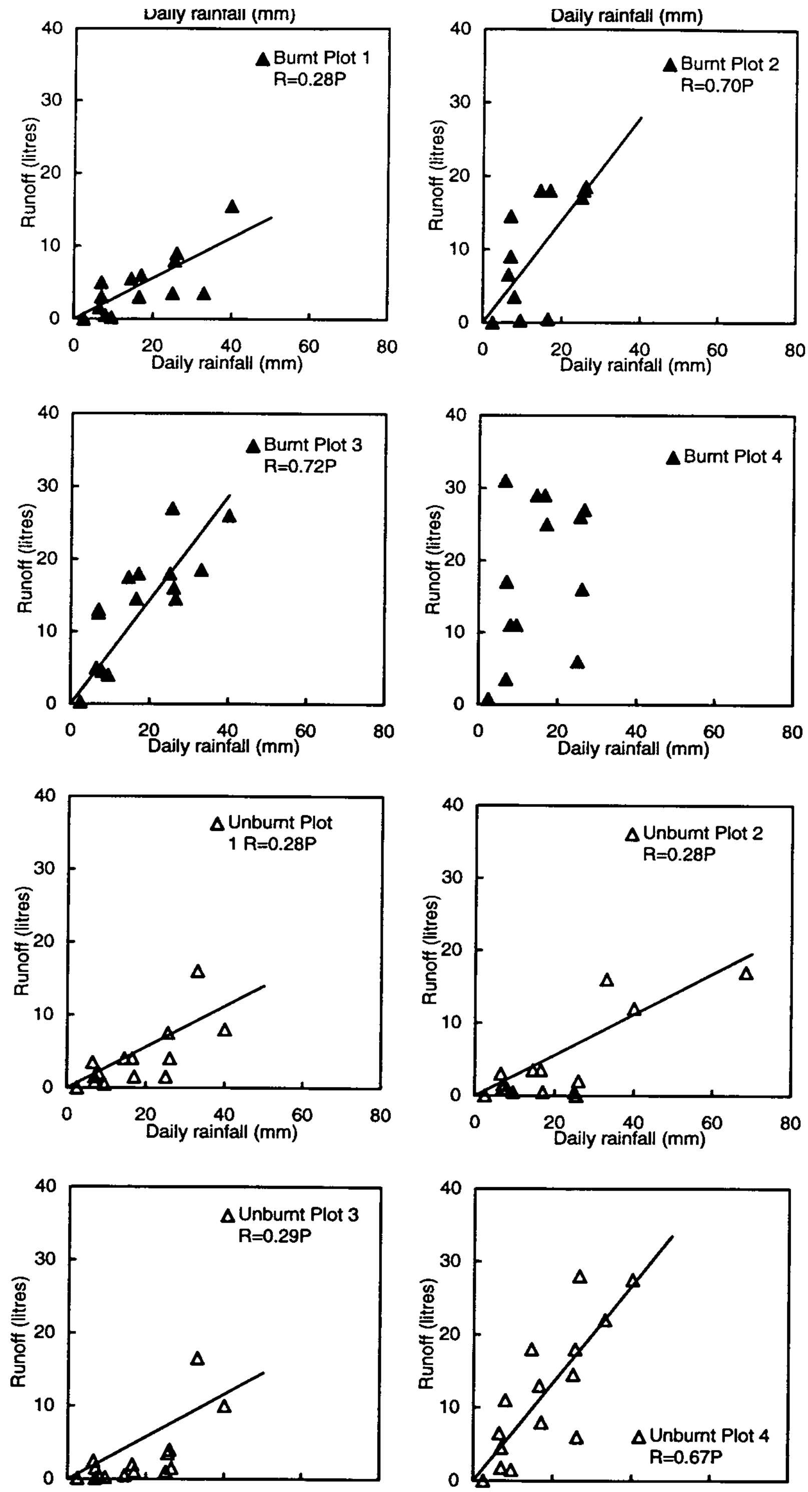

Figure 3. Daily rainfall (P) and runoff (R) relationships for plots at the burnt and unburnt sites

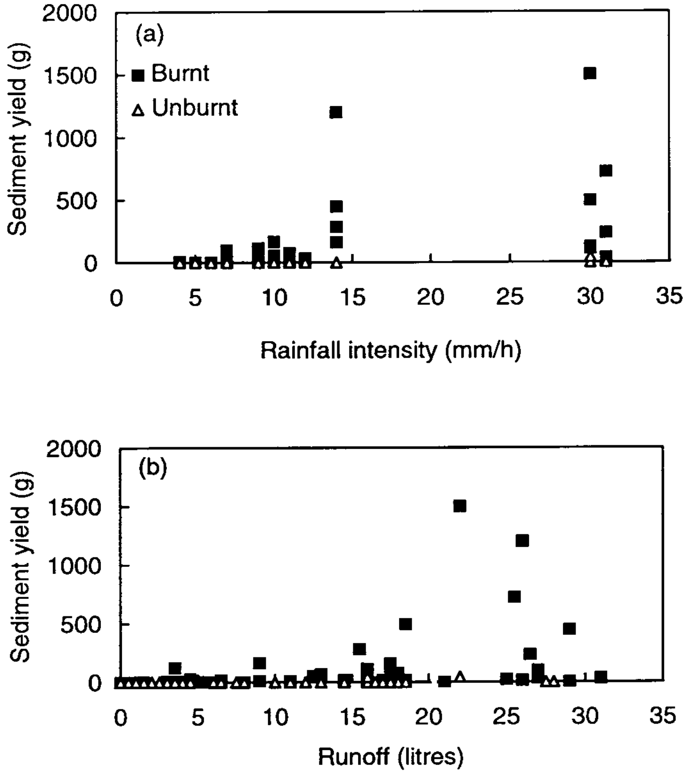

Figure 4. Plot sediment yield for burnt and unburnt plots as a function of (a) rainfall intensity, and (b) runoff volume

Sediment yield

Twelve of the sixteen runoff events produced sediment in the troughs of the burnt site, but only event 5 produced a small amount of sediment at the unburnt site (Figure 2c; Table II). Thus there was a vast difference in sediment yield between the sites. The troughs at the burnt site each received an average of 1·5 kg of sediment over the 10-month period. Events 5, 7 and 8 produced the most sediment, with average event yields of 200–500 g per plot. These three events had both the highest event rainfall and the highest 30 min rainfall intensities. However, they were not necessarily the largest runoff events, as long duration, low intensity events such as events 3, 12 and 16 produced much runoff but little sediment.

Sediment started to move on the burnt plots above a 30 min rainfall intensity of 7 mm/h (Figure 4a) with a sharp increase in sediment yield above an intensity of 13 mm/h. Sediment also moved at times when plot runoff exceeded 3 litres, and yields rose sharply above 15 litres of runoff (Figure 4b). Low sediment yield for plot runoff of >15 litres occurred for events where rainfall intensity was low. This behaviour conforms to the common observation that rain drop impact detaches sediment from the surface and that overland flow is largely responsible for transport once it is detached (Ellison, 1944). Sediment was only produced from the unburnt plots at a 30 min rainfall intensity of 30 mm/h and a plot runoff of 22 litres.

No evidence of sediment export from the burnt catchment was found. No sand was found deposited near the catchment gauging station, nor was any found deposited on the flat area at the foot of the catchment.

DISCUSSION

Comparing results from the burnt and unburnt sites isolates the influence of fire on runoff and erosion, assuming that fire dominates over other differences between the two sites. This assumption seems reasonable given the magnitude of the differences in the results and the similar landforms, soils and vegetation of the two sites. The slightly lower gradient of the unburnt plots is the largest difference, but all plots have low gradients compared with the range found in this landscape.

Runoff

The fact that small rainfall events gave runoff from plots at both sites, and the simple proportional relationship between rainfall and runoff, suggests that at least part of the upslope contributing area to each trough was essentially impermeable. These areas appear to produce runoff immediately, disregarding the small amount of rainfall lost to depression storage. Based on this assumption, the contributing areas of runoff to each trough vary from 0·2 to 0·7 m^2, much smaller than the potential contributing areas of approximately 20–40 m^2. Thus the dominant runoff process is Hortonian overland flow, but with a very patchy distribution on both hillslopes.

Given the sandy textured soils, the most likely reason for patchy impermeability is surface hydrophobicity. The 1·5–3 times greater runoff from the burnt plots can be attributed to fire creating larger and more intense patches of hydrophobicity, as indicated by the longer water drop penetration times.

Locally produced runoff infiltrated further downslope during all but the largest recorded rainfall events, for either there was no catchment runoff or it was less than that recorded in the four troughs. Water could infiltrate either along macropores or on hydrophilic patches. Substantial catchment runoff required an event with a recurrence interval of close to 1 year, but we do not know whether that runoff was generated from close to the catchment outlet or from connection to impermeable patches upslope. There are, however, no indications of systematic changes in runoff generation down the hillslope, since there are no obvious catenary sequences to the soils, or consistent trends in runoff volume when moving downslope from plot 4 to plot 1. Thus, the patchy pattern of runoff resulted in the fire having a large effect on local runoff generation but not necessarily on catchment-scale runoff, a result found elsewhere (Kutiel and Inbar, 1993; Scott, 1993).

There is no indication that runoff generation at the burnt site was recovering to unburnt levels during the 10-month monitoring period. The time-series of Figure 2 shows consistent differences between the burnt and unburnt plots throughout the monitoring period. Furthermore, there is no indication in the rainfall versus runoff graphs (Figure 3) that lower than predicted runoff is associated with events towards the end of the monitoring period. The dry conditions at Sandy Point following the fire may have helped maintain differences in runoff generation between the burnt and unburnt sites. Long, gentle wetting conditions are required to remove hydrophobicity, and these often occur in moist winters (Crockford *et al.*, 1991).

Sediment yield

The plot data are fairly crude in terms of trying to interpret erosion processes since they record only total runoff and sediment yield per event, but there were substantial overlaps in plot runoff for individual events between the two sites. This allows us to separate an increase in sediment yield owing to increased runoff from that owing to decreased surface resistance to erosion after the fire, and to compare erosion processes between sites.

Substantial resistance to both rain drop impact and sediment transport by overland flow can be inferred from the lack of sediment yield from the unburnt plots, despite the frequent runoff. This resistance to erosion can be described as a threshold for significant sediment transport, of at least 22 litres of plot runoff and a 30 min rainfall intensity of at least 30 mm/h. Sediment yield from the burnt plots during events of >7 mm/h 30 min rainfall intensity and 3 litres of plot runoff suggest that resistance to both rain drop impact and sediment transport by overland flow was greatly reduced.

It is not clear whether there is a measurable threshold for sediment transport at the burnt site, since several of the smallest events did yield sediment. Consequently, resistance to erosion is probably equivalent to the grain resistance of sand to detachment and transport. The much higher resistance to sediment transport at the unburnt site demonstrates the effectiveness of grass and litter cover in protecting the surface. The largest and most intense rainfall events recorded sharp increases in sediment yield from the burnt plots, but had low proportional differences in plot runoff between the sites. Thus, decreased ground cover was the critical factor that increased sediment movement after the fire.

The data of Blong *et al*. (1982) also provide support for low resistance to erosion on plots after fire. They recorded their highest individual sediment yields of over 1000 g from 8 m^2 plots in a storm with a 30 min rainfall intensity of 30 mm/h. Atkinson (1984) recorded sediment yields of 17–140 g/m^2 from 16·5 mm of rainfall in 45 min, which is also consistent with our results.

Sediment yield from the plots declined in the second half of the monitoring period. This could be taken as evidence for recovery of the burnt catchment and increasing resistance to sediment transport, but was more likely a response to low rainfall intensities during the second half of the monitoring period. Sediment was still delivered from the burnt plots from small events but none came from the unburnt plots, suggesting that the burnt site had not fully recovered. The continuing sediment yield from the burnt plots also showed that sediment was still available for transport with no suggestion of sediment exhaustion during the monitoring period.

The fire resulted in local redistribution of sediment but little if any sediment was delivered from the burnt hillslope, because of the low catchment runoff. The pattern of plot runoff suggests that the measured sediment yields came from small patches within a metre or so of each trough. Events of the order of 1 year recurrence interval or larger would be required to deliver sediment from the hillslope catchment, since it is only these events that would generate catchment runoff.

Nevertheless, not much sediment needs to be exported from the catchment to record accelerated erosion, because long-term erosion rates in the native *Eucalyptus* forests are very low; of the order of 10^{-3} mm/y (Bishop, 1985; Prosser *et al*., 1994). Fires have long been relatively frequent in these forests, raising the question of the probability of fire-accelerated erosion. Relatively mild fires appear to have no influence on long-term erosion rates. Increases in the frequency of mild fires as a result of Aboriginal burning of *Eucalyptus* forests, recorded as large increases in the charcoal content of deposits, are not associated with any increase in rates of valley alluviation (Prosser, 1990). If, however, a moderately intense fire is followed by a large storm event, such as the 1 in 10 year events recorded by Atkinson (1984), then annual soil erosion can be 1000 times larger than the longer term average.

Association of extreme rainfall with a moderately intense fire is probably rare, as it requires the close association of two low probability events: intense fire and a large magnitude storm. There is likely to be a lower than average probability of high rainfall following fire as intense fires are associated with drought conditions. For example, seasonal weather patterns in Australia are controlled in part by global patterns of atmospheric and oceanic circulation measured as the southern oscillation index. Negative values of the southern oscillation index, known as El Niño events, are associated with both drought and high fire frequency (McBride and Nicholls, 1983; Skidmore, 1987). It is probably no coincidence that Brown (1972), Good (1973), Blong *et al*. (1982), Prosser (1990) and this study all noted drier than average conditions in the year following fire. Consequently, the probability of accelerated erosion following fire is probably much less than indicated by the recurrence interval of intense storms.

There are no long-term records in Australia of the frequency of fire-induced accelerated erosion, but studies in the United States show that fire-associated pulses of sediment have a 500–1000 year recurrence intervals (Meyer *et al*., 1995; Rhodes and Davis, 1995). Further insight into this issue could be gained by analysing the combined probabilities of intense fire and rain.

CONCLUSIONS

Comparing plots at burnt and unburnt sites has shown how fire alters runoff and erosion processes in native *Eucalyptus* forests. Runoff at both sites was generated from small patches affected by soil hydrophobicity, which was enhanced by the fire, resulting in greater runoff on the burnt plots. Soil hydrophobicity had little effect on runoff at the hillslope scale, where rainfall of approximately 1 year recurrence interval or greater is required to generate significant runoff.

The fire greatly reduced the resistance of the surface to erosion, more through complete removal of ground cover and burning of organic matter than from increased runoff. Sediment was only redistributed locally, however, and was not exported from the hillslope.

Increased runoff and sediment movement were still greater on the burnt plots 10 months after the fire, and it probably takes at least a year for surface recovery. Nevertheless, recovery of runoff and surface resistance were poorly defined by relying on natural rain alone. Better definition of recovery processes would be possible using controlled rainfall simulator experiments, but of course these do not record the actual sequence of events following a fire. Monitoring or experiments at the plot scale help us understand runoff and erosion processes, but these results may not reflect the effects of the fire at the more significant hillslope and catchment scales.

Comparison of our results with previous studies shows that moderately intense fires, such as the 1994 Sydney fires, can produce substantial erosion if rainfall events of 1-year recurrence interval, and possibly as high as 10-year recurrence interval, follow in the year after the fire. Such events are of low probability and did not occur after the 1994 Sydney fires. So, whilst there were legitimate concerns over accelerated erosion these were not realized. Isolated areas of the 1994 Sydney fires experienced an extreme intensity burn (Zierholz *et al*., 1995), where accelerated runoff and erosion were observed and could be expected even considering the lower than average rainfall.

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