# Suspended sediment yield following wildfires in a mixed species eucalypt forest, southeastern Australia

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**Abstract** In June 2001, flow and suspended sediment monitoring equipment was installed at the outlets of four study sub-catchments in Kangaroo River State Forest, southeastern Australia. A moderate severity wildfire in October 2001 burnt 94% of a 443-ha sub-catchment and the same wildfire, combined with an earlier fire in August 2001, burnt through 61% of the adjacent 367-ha sub-catchment. Neither of the remaining sub-catchments experienced these wildfires. The 2001 wildfires occurred during a drought year which was followed by an extended period of low rainfall. Substantial flows did not occur in either of the burnt sub-catchments until February 2003. As a consequence, suspended sediment yields in the immediate post-fire period were minimal and not significantly different in the burnt and unburnt sub-catchments. A substantial sediment pulse was generated during the summer rains of February (223.7 mm) and March (200.5 mm) 2003 in all sub-catchments, with sediment responses being similar in the burnt and unburnt areas. This case study illustrates the importance of the timing and magnitude of post-fire rainfall events in determining the likelihood of significant sediment transport following wildfires.

**Key words** wildfire; drought; catchment response; Kangaroo River; southeastern Australia

## INTRODUCTION

The rate of sediment transfer commonly increases following wildfires (Zierholz *et al*., 1995; Prosser & Williams, 1998), especially when high-intensity rainfall events occur before vegetation cover has become re-established (Smith & Dragovich, 2008). The sediment response to post-fire conditions is also dependent on fire severity (Prosser, 1990; Dragovich & Morris, 2002) with low severity and prescribed burns often resulting in only minor erosion. Regardless of fire severity, any high intensity rainfall event occurring post-fire is likely to generate accelerated sediment redistribution. In the higher rainfall areas of Australia, fuel loads accumulate during wetter years and these areas are prone to wildfires during extremely hot summers and/or drought periods. Against this context, this study investigated suspended sediment yields from adjacent sub-catchments that had been partly burnt, almost completely burnt, or were entirely unburnt, with the aim of identifying potential differences in fire-generated accelerated erosion related to the spatial extent of burnt areas.

## STUDY AREA

The study was carried out in Kangaroo River State Forest in southeastern Australia. Monitoring equipment was installed in four adjacent sub-catchments (two sets of paired sub-catchments). The terrain is dissected by V-shaped valleys with minimal development of flood plains in the two northern sub-catchments, but small pockets of flood plain deposits and benches exist in the larger southern sub-catchments. In most areas the generally steeply-sloping terrain supports a dense understory and mixed species eucalypt forests dominated by Spotted Gum (*Corymbia maculata*), Sydney Blue Gum (*Eucalyptus salinga*), Blackbutt (*E. pilularis*) and Flooded Gum (*E. grandis*), along with stands of Grey Ironbark (*E. paniculata*) and Grey Gum (*E. propinqua*) on summits and upper slopes. On wet lower slopes, White and Red Mahogany (*E. acmenoides* and *E. resinifera*) occur, especially in shaded locations (Forestry Commission of NSW, 1989). Prior to 2001, selective harvesting for saw-logs took place before 1993 in the two southern (unburnt) sub-catchments and some harvesting probably occurred in the northern (burnt) sub-catchments in the 1970s.

Local soils are dominated by the Black Mountain soil landscape which is characterised by well-drained structured Yellow Earths and Brown Earths (Milford, 1996), often occurring in deep (>150 cm) units. Milford (1996) categorised the Black Mountain and most other soil landscapes in the study sub-catchments as having high to very high erodibility, with only relatively small areas described as having low to moderate erodibility.

The climate is subtropical, with maximum rainfall occurring during summer when thunderstorm activity is common. Average annual rainfall at Coffs Harbour (Australian Bureau of Meteorology climate station 059040), about 40 km southeast of the study area, is 1693 mm. Average monthly temperature is 13.2°C in July and 23.2°C in January and February. Since the commencement of the study in 2001, and up to 2009, annual rainfall at the raingauge located in the southwest of the sub-catchments has averaged about 1400 mm. The years included in this study (June 2001 to June 2004) generally experienced low annual rainfall, with totals for the 12 months from June to May in each year being 643 mm to May 2002, 958 mm to May 2003, and 1032 mm to May 2004.

## METHODS AND MATERIALS

Flow and suspended sediment gauges were installed at the outlets of four adjacent sub-catchments. Two sub-catchment "pairs" were designed to assess the impacts of selective logging, each pair comprising a "Control" and an "Impact" sub-catchment. Following the installation of gauges in June 2001, a low to moderate severity wildfire in October 2001 burnt 94% of a 443-ha sub-catchment called Impact 1 (I-1). The same wildfire, combined with an earlier fire in August 2001, burnt through 61% of the adjacent 367-ha sub-catchment called Control 1 (C-1) (Fig. 1). The 2001 fires were the most recent to have affected these two northern sub-catchments (C-1 and I-1). Ten near-surface soil samples collected in partly burnt C-1 contained varying amounts of charcoal, but the presence of charcoal, which is readily transported, was not confined to the burnt areas. The two southern sub-catchments called Control 2 (C-2) and Impact 2 (I-2) were not burnt in the 2001 fires.

Streamgauging stations were installed at the outlet of each sub-catchment, while both a tipping bucket (pluviometer) and manual raingauge were installed and maintained at a central location (Fig. 1). Streamgauges were located on bedrock controls upstream of tributary junctions on each stream and in similar geomorphic settings. Each station was instrumented with an automatic pump water sampler (ISCO 3700), a datalogger (Datataker DT50), pressure transducer and staff gauge, powered by 12V batteries charged by a solar panel. Stream height was logged at six-minute intervals and converted to discharge using rating curves derived from velocity–area gaugings undertaken at a range of flows. Water samples, 500 mL in volume, were automatically pumped from each stream by a stage-activated sampler (ISCO 3700 model) throughout flood events, on the rising and falling limbs of the hydrograph. In addition, weekly water samples were pumped from each stream during periods of baseflow. At each data download visit (fortnightly or more frequently during floods) water samples were retrieved from the automatic samplers, refrigerated and couriered to the laboratory where they were analysed for turbidity and suspended sediment concentration according to standard methods (APHA, 1998). The comprehensive flood and baseflow sampling facilitated accurate estimates of suspended sediment loads.

Rainfall figures for all comparisons were those recorded at the gauging station installed in the southwestern part of the study area in 2001. Initial comparisons were made for streamflow and sediment yields between sub-catchments C-1 (61% burnt) and I-1 (94% burnt) (Fig. 1). Subsequently both burnt sub-catchments 1 (C-1 and I-1) were compared with unburnt sub-catchments 2 (C-2 and I-2). These records were investigated for the period from June 2001 to June 2004, which included an initial low rainfall period and two high rainfall events (February–March 2003 and January–March 2004).

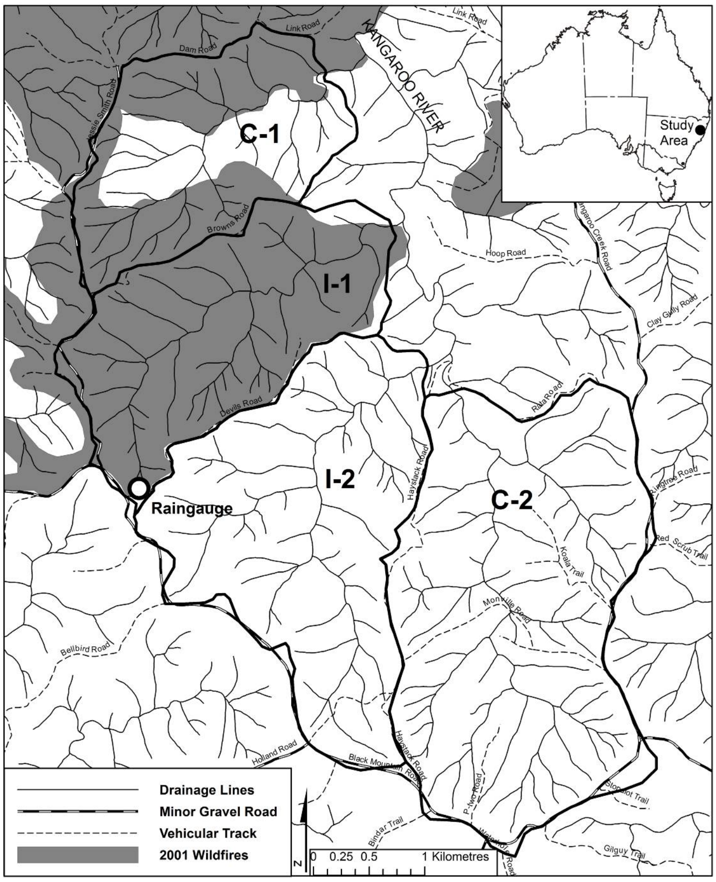


**Fig. 1** Extent of the 2001 wildfires in the study sub-catchments in Kangaroo River State Forest.

## RESULTS

### Partly burnt (C-1) and burnt (I-1) sub-catchments

Monthly rainfall exceeded 100 mm on only three occasions between June 2001 and January 2003, giving an average monthly rainfall for this period of 49.6 mm compared with the long-term average at Coffs Harbour of 141.1 mm. Streamflow was negligible or absent in both sub-catchments over this period: C-1 recorded 10 months with zero flow months, and I-1, 9 months. In February and March 2003, rainfall totalled 223.7 mm and 200.5 mm, respectively, and these falls generated substantial streamflow in both sub-catchments. Streamflow was greater in the partly burnt (C-1) sub-catchment than in the nearly completely burnt (I-1) one. Subsequent minor peaks in rainfall and streamflow occurred in May 2003 and January 2004, with a second major peak in March 2004. The high rainfall in January 2004 (290 mm) followed a relatively dry period of several months and streamflow did not respond substantially until further heavy rain fell (256 mm) in March 2004 (Fig. 2).

Given the almost complete absence of streamflow until February–March 2003, recorded sediment yields over that period were very low. Yields were similar in both sub-catchments for these minor rainfall events. In March 2003, yields were greater in the partly burnt (C-1) than in the burnt (I-1) sub-catchment, and the same pattern between the sub-catchments was evident in the second high rainfall period of January–March 2004 (Fig. 2).

Streamflow and sediment yield were thus both greater for the partly burnt (C-1) than for the burnt (I-1) sub-catchment (Fig. 3). Cumulative streamflow patterns for sub-catchments C-1 and I-1 were similar, although the partly burnt area (C-1) had consistently higher values than the burnt (I-1) sub-catchment (Fig. 4). The two substantial rainfall events over the study period were reflected in steep, short-term increases in cumulative streamflow.

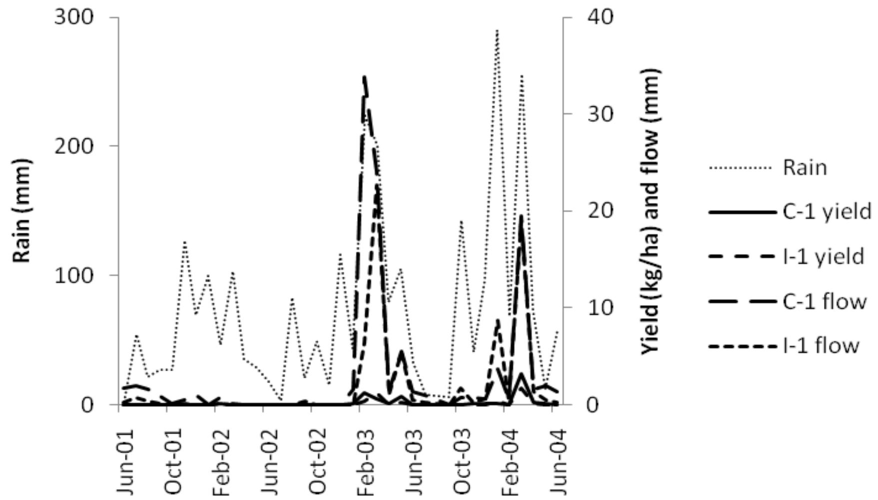


**Fig. 2** Rainfall, sediment yield and streamflow in the partly burnt (C-1) and burnt (I-1) sub-catchments.

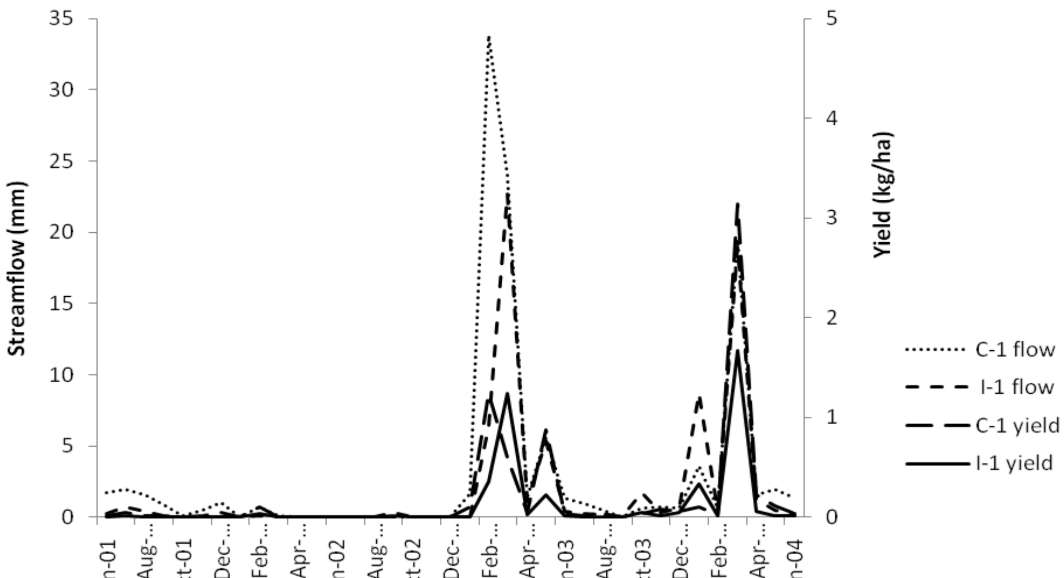


**Fig. 3** Streamflow and sediment yield in the partly burnt (C-1) and burnt (I-1) sub-catchments.

## Burnt sub-catchments C-1 and I-1 (Sub-Cs1), and unburnt sub-catchments C-2 and I-2 (Sub-Cs2)

The overall pattern of rainfall and streamflow for the burnt and unburnt sub-catchments was dominated by the substantial rainfalls in February–March 2003 and January–March 2004. Although streamflow in the unburnt sub-catchments (Sub-Cs2) recorded more than double the rates in the burnt sub-catchments (Sub-Cs1) in the 2004 heavy rains, the high March 2004 sediment yields were similar for both sets of sub-catchments (Fig. 5). Until that event the unburnt sub-catchments (Sub-Cs2) generally registered higher sediment yields. Cumulative yields for both the burnt and unburnt sub-catchments showed marked increases in response to the major rainfall events in 2003 and 2004, with the unburnt sub-catchments having higher streamflows and higher sediment yields (Fig. 6).

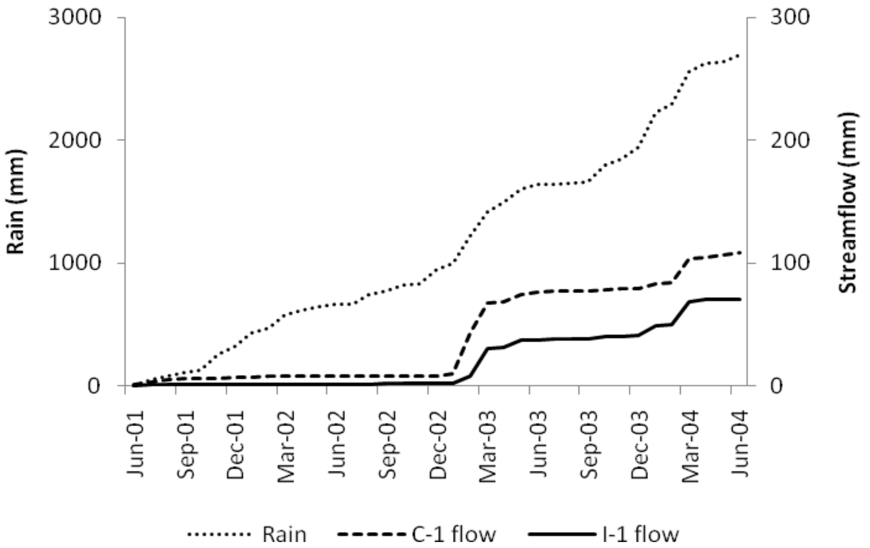


**Fig. 4** Cumulative rainfall and streamflow in the partly burnt (C-1) and burnt (I-1) sub-catchments.

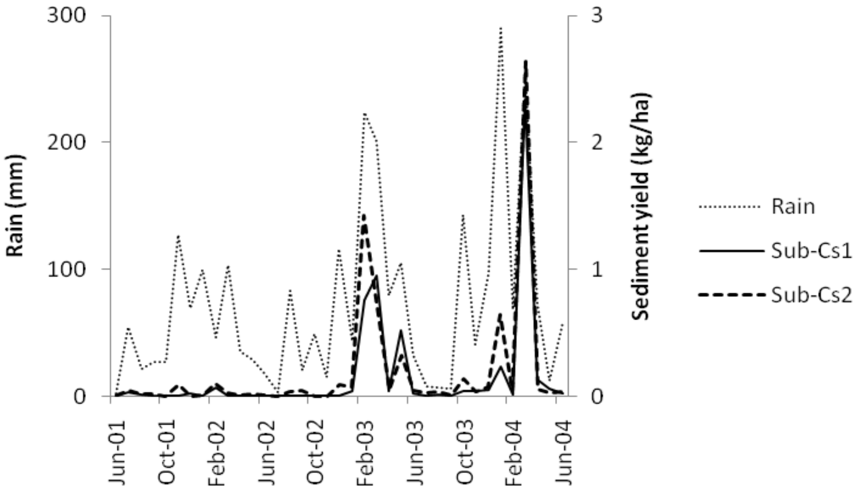


**Fig. 5** Rainfall and sediment yield in burnt sub-catchments C-1 and I-1 (Sub-Cs1), and unburnt sub-catchments C-2 and I-2 (Sub-Cs2).

## DISCUSSION

Burnt areas are expected to generate accelerated runoff to channels and greater suspended sediment loads (e.g. Moody & Martin, 2001; Lane *et al.*, 2006; Reneau *et al.*, 2007; Sheridan *et al.*, 2007). Such post-fire sediment may be delivered to streams by slope wash and/or by erosion of channel beds or banks during higher flows. More extensively burnt areas could be expected to produce greater runoff and sediment transport than little affected or unburnt catchments. In the February–March 2003 rains in this study, streamflow was greater in partly burnt sub-catchment C-1 than in nearly completely burnt I-1 (two-month totals of 57.8 mm and 29.0 mm, respectively). Sediment yields were similar for both sub-catchments (two-month totals of 1.8 and 1.6 kg/ha, respectively). In the heavy rainfalls of March 2004, streamflow in the two sub-catchments was similar (19.5 and 19.0 mm). However, sub-catchment C-1 with 61% of its area burnt in wildfires in 2001, generated considerably higher sediment yields than adjacent sub-catchment I-1 with 94% of its area burnt (3.14 kg/ha compared with 1.67 kg/ha). This response may be partly attributable

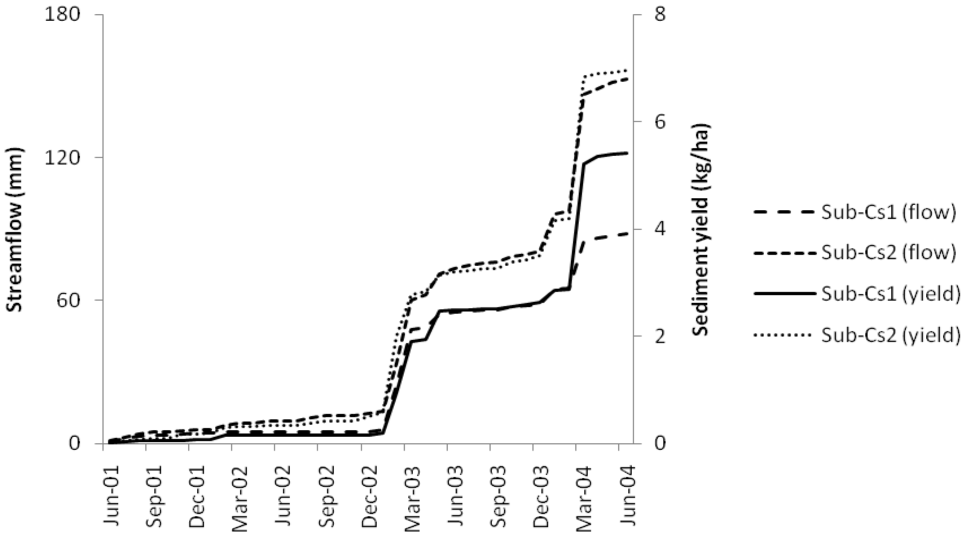


**Fig. 6** Cumulative sediment yield and streamflow in the burnt sub-catchments C-1 and I-1 (Sub-Cs1), and unburnt sub-catchments C-2 and I-2 (Sub-Cs2).

to the low to moderate severity wildfires and to contrasts in sub-catchment attributes which could produce varying results even in the absence of wildfire as a major landscape disturbance.

Riparian vegetation is dense in all the sub-catchments. The vegetation cover *C* values for RUSLE were estimated for 2011 using NDVI-based analysis of vegetation (Jamshidi *et al*., 2012). Low *C* values occurred along stream lines reflecting the dense vegetation cover in those portions of the study area. NDVI analysis of the *C* factor was applied to 2005 images and mean *C* values for the partly burnt (C-1) and burnt (I-1) sub-catchments were estimated at 0.0034 and 0.0032, respectively. Mean *C* values for both unburnt sub-catchments (C-2 and I-2) were lower (0.0021 and 0.0025). Riparian vegetation could be expected to intercept hillslope sediment delivery in sub-catchment C-1, as this was the unburnt area in the 2001 fires. Despite this, sub-catchment C-1 had higher sediment yields than sub-catchment I-1. In addition to the importance of vegetation cover is the presence of a litter layer, which may be capable of providing substantial moisture storage for post-fire rainfalls (Leighton-Boyce *et al*., 2007), thereby reducing overland flow. Previous work has suggested that augmented flows following heavy rains lead to greater mobilisation of channel bed/bank deposits (Moody & Martin, 2009) and this may have contributed to the sharply increased sediment yields noted in the two post-fire high rainfall events that were apparent in both the burnt and unburnt sub-catchments. Sheridan *et al*. (2011) proposed that sediment sources shift from being slope-dominated to channel-dominated as vegetation recovers in the years following fires. Accelerated amounts of hillslope-derived sediments are transferred post-fire, but not necessarily transported into channels (Shakesby *et al*., 2007); temporary sediment sinks on hillslopes probably become increasingly important as fire severity diminishes.

Sediment transfer at the plot scale cannot be readily translated to sediment yield at catchment scales (Lane *et al*., 2006), but sediment response patterns to post-fire rainfall events are similar at the two scales. Using runoff troughs to capture mobilised sediment, Prosser & Williams (1998) found that sediment yields for burnt plots increased markedly with high intensity rainfall, results that were consistent with earlier rainfall and plot data on post-fire sediment transfer reported by Blong *et al*. (1982) and Atkinson (1984), and observations by Zierholz *et al*. (1995). Nyman *et al*. (2011) found that high intensity storms following wildfires in small (<100 ha) and steep (25° to 35°) catchments generated considerable amounts of sheet erosion which made a large contribution to suspended sediment yield, and Lane *et al*. (2006) also noted that one or two heavy thunder-storms were responsible for mobilising and transporting most of the post-fire sediment load. The impacts of low intensity rainfalls, which encourage vegetation regrowth following fire and are associated with minimal erosion and negligible flows (Condina *et al*., 1984; Chessman, 1986), are less frequently reported. These conditions were observed during this study in the Kangaroo River State Forest.

During this study, the combined unburnt sub-catchments (C-2 and I-2: called Sub-Cs2) generally recorded higher streamflows and sediment yields than the burnt sub-catchments (C-1 and I-1: called Sub-Cs1). Drainage density was a potential variable influencing these yields. However, drainage density was greatest in the partly burnt (C-1) (5.035 km/km$^2$) and lowest in the burnt (I-1) (4.137 km/km$^2$) sub-catchment. Corresponding values for the unburnt sub-catchments (C-2 and I-2) were 4.548 km/km$^2$ and 4.251 km/km$^2$, respectively. Based on 10-m pixels in a DEM, the proportion of each sub-catchment covered by slopes exceeding 15° was nearly 65% for both partly burnt C-1 and unburnt C-2, compared with over 70% for both I-1 (burnt) and I-2 (unburnt). Slopes greater than 30° covered between 8% and 10% of I-1 and I-2, respectively. Of the four sub-catchments, burnt I-1 had the lowest drainage density and the greatest proportion of slopes exceeding 15°, while partly burnt C-1 had the highest drainage density and lowest proportion of steeper slopes. The contribution of these terrain characteristics to observed sediment yield differences is uncertain as the extent to which slope steepness is offset by drainage density is not known.

Like many hydrological studies focused on landscape disturbance, this experiment was not able to assemble lengthy pre-fire flow and sediment yield records due to the short period between the installation of monitoring equipment and the wildfires. A longer pre-fire record would have allowed for robust comparisons between pre- and post-fire responses in both burnt and unburnt sub-catchments, as was possible for paired catchments in Victoria, Australia (Lane *et al*., 2006; Bren, 2012). The lack of robust baseline data is a problem for many paired catchment studies across the world. A further constraint on interpreting the observed differences between the burnt and unburnt areas used in this study was the likelihood of rainfall variations over the individual sub-catchments, especially relating to the incidence and intensity of highly localised summer thunderstorms.

## CONCLUSION

This study investigated possible differences in sediment yield responses between partly burnt, almost completely burnt, and unburnt sub-catchments. The expectation of greater sediment yields in sub-catchments most affected by wildfire was not observed. Although part of the reason for this may have been topographic, hydrological or soil differences between the individual sub-catchments combined with the low to moderate intensity of the fires, the intervening period between equipment installation in June 2001 and the February–March 2003 rain event included only six (non-consecutive) months with rainfall of less than 25 mm. This consistent presence of moisture delivered in low intensity falls in the 20 months following fires allowed for the re-growth of forest groundcover and produced subdued streamflow and sediment yield responses to wildfire. The results of this study therefore suggest that the timing and intensity of post-fire rainfall events are important determinants of erosion and sediment transport responses to wildfires.

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