Sediment and organic matter transfer following bushfires in the Blue Mountains, Australia

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Abstract The fire regime in eucalypt forest and woodland in Australia has changed over the last 200 years from being characterized by frequent low intensity burns, to generally less frequent but higher intensity fires. Spatial variability in the transfer of sediment, organic matter and leaf litter was monitored on 10 plots for 6 months following fires of high, moderate and low intensity. Sediment and organic matter movement was substantially higher on intensely and moderately burnt areas than on unburnt (low fire intensity) areas. Leaf litter was recorded in largest amounts on moderately burnt areas where additional post-fire leaf fall from singed vegetation occurred following strong winds. Fire intensity is important in contributing to spatial variability in the post-fire transfer of sediment, organic matter and leaf litter. Burnt vegetation may be temporarily retained in on-slope litter dams and subsequently incorporated into bench or flood plain deposits within channels.

Key words bushfires; sediment plots; soil erosion; slopewash; eucalypt forest; burnt vegetation

INTRODUCTION

Bushfires are common in Australia and vegetation has adapted to this pattern by developing an ability for rapid post-fire regeneration or fire-dependent seed dispersal (Gill, 1981). Traditionally the fire regime has been characterized by frequent low intensity burns (Worboys & Gellie, 1989), often lit deliberately by Aboriginal hunters or ignited by lightning strikes. Following European settlement forests and woodlands were cleared for cropping and grazing. In some of the remaining forests in national parks, vegetation is subject to periodic low intensity control burns but the general pattern is towards less frequent but higher intensity fires.

In the Blue Mountains to the west of Sydney the vegetation is predominantly eucalypt woodland and forest (*Eucalyptus* spp.) and high intensity bushfires have become a recurring feature of the region (Cunningham, 1984). In the 1994 fires it was estimated that more than 800 000 ha were burnt out (Cheney, 1995). Apart from major fires that are often associated with droughts, numerous more localized outbreaks contributed to the high number of fires recorded in the region: more than 400 bushfires occurred during a 28-year period of accurate records (Worboys & Gellie, 1989).

Bushfires in eastern Australia are followed by substantial increases in runoff, sediment transport, and movement of organic matter (burnt vegetation) (Blong *et al.*, 1982; Atkinson, 1984; Prosser, 1990; Prosser & Williams, 1998). By influencing runoff rates and sediment transfer, fires are indirectly linked to channel flow, bank erosion, and in-channel sediment movement. Fire intensity is known to affect erosion in the post-fire period in Australia (Prosser, 1990; Prosser & Williams, 1998; Zierholz *et al*., 1995) and elsewhere (Simanton *et al.*, 1990; Kutiel & Inbar, 1993). This study investigates spatial variability in sediment and organic matter transfer on hillslopes subjected to high, moderate and low intensity fires.

STUDY AREA

The Blue Mountains form a dissected plateau surface composed predominantly of nearly horizontally bedded sandstones with some shale lenses and occasional basalt flows (Conaghan, 1980). Slopes take the form of a complex series of benches bounded by rocky outcrops; this segmentation reduces effective slope length and increases temporary on-slope storage of sediment (Erskine & Melville, 1983). Soils are mainly thin and sandy on the slopes, with some deeper earthy sands on the plateau surface. At the study sites, maximum soil depth was 45 cm. Vegetation is classified as having a Sydney sandstone ridgetop woodland structure (Benson, 1992). Of the canopy species, *Eucalyptus* spp and *Angophera costata* dominate.

At the study site near Faulconbridge, about 75 km west of Sydney, average annual rainfall over 57 years of unofficial records is 1184 mm (Derbyshire, 1994, personal communication). Three hillslopes were selected for study, on the basis of all being within a distance of 2.5 km, and having the same geology, soils, elevation, gradients, vegetation structural type (as identified in aerial photographs dated 1991), and aspect (south facing). Each hillslope had different fire intensities as indicated by fire effects on vegetation. In high intensity burn areas, no canopy leaves or pre-fire ground cover remained; in moderate intensity burn areas, some canopies remained intact but most were partly burned or singed and most understorey plants were lost. In both of these areas the organic litter layer had been replaced by a charcoal and ash layer. These hillslopes were contrasted with an area which was unburnt in the 1994 fires but had a low intensity control burn in 1992; the organic litter layer here was at least 2 cm thick.

METHODS

High, moderate and low intensity burns were present within the study area. Each of the 10 monitored runoff plots was located about 3 m downslope from a sandstone cliff 1–3 m high. For areas of high and moderate intensity burns, one open and one closed plot was installed in each of the upper and lower slope positions (two open and two closed plots for each fire intensity). Plots were located at about 60 m from the crest for both upper positions, and about 30 m from the base of slope for lower positions. Slopes were 240 and 270 m long for high and moderate intensity burns respectively. The unburnt area had one open plot on the upper slope and one on the lower; installing closed plots would have caused too much disturbance to sediment and vegetation.

Plot design followed that described by Riley *et al*. (1981). All plots had a concrete apron leading to a collection drum, with sediment and organic matter being collected from both the drum and the concrete apron. Open plots measured sediment and organic matter crossing a 2-m apron oriented normal to the slope. Closed plots were also constructed with an apron 2 m wide; these plots measured runoff and sediment from an area of 8 m^2.

Over the six-month monitoring period collections were made 11 times, following substantial rainfall. The number of potential sediment movement events was reduced by dry conditions, with a total of only 58 mm of rainfall being recorded for the last four months of the study period. Organic matter percentage was based on loss on ignition values for all material less than 4 mm in diameter, beyond which size organic matter was designated as leaf litter.

SPATIAL VARIABILITY AND FIRE INTENSITIES

Sediment (slopewash) transfer

Four plots for each burn condition were located in areas of high, moderate and low fire intensities. Because of incomplete records for organic matter for one plot on the unburnt (low intensity) area, only one upper and one lower slope plot was used making a total of 10 plots for reporting sediment and organic matter transfer. “Sediment” refers to slopewash and excludes visibly bioturbated material (mainly composed of edges of ant mounds impinging onto the plot aprons).

Total sediment collected over the six-month period on the four high intensity burn plots was 4470 g (average 1118 g per plot), compared with 2397 g (average 599 g per plot) for the four moderately burnt plots and 142 g (average 71 g per plot) for the two low (unburnt) intensity burn plots (Fig. 1(a)). For all plots, maximum sediment amount recorded in one collection was 840, 292 and 23 g respectively for high, moderate and low intensity burns. Maxima for the high and moderate intensity burns were recorded for the same collection day but the maximum recorded for the unburnt plots occurred on a different day, two months later.

Over the study period, between-plot differences in sediment movement were considerable even within areas having similar burn intensities. One plot in each of the intensely and moderately burnt areas recorded amounts which were substantially greater than for the other three plots. Unburnt areas had very low rates of sediment movement.

Factors contributing to between-plot variation for given fire intensities may have included slope position and plot type. The expected higher sediment transfer for open plots was recorded for intensely burnt areas where combined sediment from the two open plots was 2.2 times that for closed plots. Surface conditions further upslope of the plot may have influenced this result. This explanation however would not hold for the moderate intensity burn areas where the highest sediment transfer was registered for a closed plot, and where closed plots registered 2.0 times the sediment collected from open plots. It was also anticipated that plots in lower slope positions would record higher runoff and sediment movement but results were not consistent. The segmented nature of the sandstone slopes probably reduced the effect of slope position on sediment transfer.

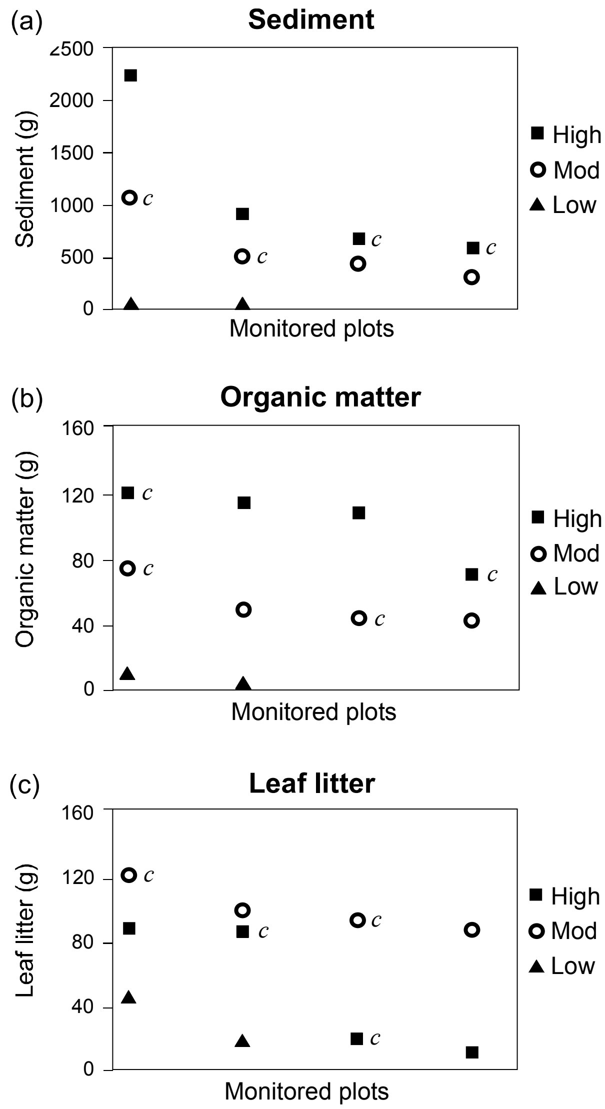

Fig. 1 Sediment (a), organic matter (b) and leaf litter (c) transfer on 10 study plots. Values for individual plots have been arranged in order of magnitude for each fire intensity (high, moderate, low). Closed plots are designated by *c*.

Organic matter transfer

Patterns of organic matter transfer were strongly linked to fire intensities. A total of 416 g of organic matter was recorded for the high intensity burn plots (an average of 104 g per plot), compared with a total of 245 g for moderately burnt areas (an average of 61 g per plot) and only 19 g (an average of 10 g per plot) for the unburnt areas. The lowest organic matter yield on the high intensity plots (71 g) was only slightly less than the largest amount recorded on a moderately burnt plot (76 g). Organic matter transfer was very low on the unburnt plots (Fig. 1(b)).

Throughout the monitoring period organic matter transfer was greatest on the high intensity burn plots, with large differences between these and the other plots occurring on three occasions. Because high intensity burns will produce substantial quantities of burnt vegetation and ash, organic matter movement during runoff events on these slopes was likely to be considerable. Fluctuations in organic matter delivery to plot collecting points was partly linked to runoff and sediment transfer, but movement of organic matter was most apparent in the earlier monitoring period when greater amounts of burnt material were still present on slopes. A secondary peak in organic matter transfer was also recorded near the end of the study, especially on the intensely burnt plots, and the downslope movement or possible destruction of litter dams may have contributed to this.

Leaf litter

Most leaf litter was collected on the moderately burnt plots, in contrast with sediment and organic matter whose movement was most pronounced on the high intensity burn areas. A total of 209 g of leaf litter was recorded for the high intensity burn plots (an average of 52 g per plot), compared with 407 g for moderately burnt areas (an average of 102 g per plot) and only 69 g (an average of 34 g per plot) for the unburnt areas (Fig. 1(c)). On the moderately burnt slopes, some incompletely burnt leaves and plant material would have remained on the ground following the fire. This leaf litter supply would have been present to a much lesser extent on the intensely burnt slopes, while leaf shedding by vegetation in the unburnt area would have been unrelated to the fires. In addition to normal leaf fall in all but the burnt-out areas, fire-affected areas would have leaves which were singed but not completely burnt, with these leaves remaining only temporarily part of the canopy. Heat- or drought-affected vegetation may also have shed leaves in the post-fire period. Fall of singed leaves continued after the fires, with occasional high-wind events being accompanied by greater leaf fall. Wind also probably re-distributed this material beyond the moderately burnt "source" areas, as temporal patterns of leaf litter transfer were similar in relative terms for most plots. Because wind as well as runoff was involved in leaf litter movement, fluctuations in leaf litter amounts did not mirror those for sediment and organic matter. Strong winds generated large amounts of leaf litter for several weeks in the fourth month of the monitoring period, a time when only moderate amounts of sediment and organic matter were collected.

DISCUSSION

Increases in downslope transfer of sediment, organic matter and leaf litter occurred in the 6 months following bushfires. Differences in sediment and organic matter were linked to fire intensities, with intensely burnt slopes yielding much larger quantities than areas with moderate or low intensity burns. On intensely burnt areas, ash and charcoal provided the only interception to post-fire rainfall, leading to high runoff rates which may have been augmented by soil hydrophobicity (Zierholz *et al.*, 1995). A strong association existed between yields of sediment and organic matter for all fire intensities. The behaviour of leaf litter was consistent with fires having accelerated the rates of leaf fall, except for intensely burnt areas where most vegetation fragments greater than 4 mm had been destroyed. In areas of moderate fire intensities, leaf litter collections were relatively high due to incomplete burning and a source of additional leaf fall (singed leaves) in the post-fire period. By extension, channel sediments are likely to be incorporating partly burnt leaf material for some months after bushfires.

Between-plot variation in collected materials on the burnt areas was considerable, despite the relatively short distances between plots. For sediment transfer, the between-plot coefficient of variation for high, moderate and low intensity fires was 59%, 50% and 18% respectively. No significant difference in sediment transfer was recorded between the plots on high and moderately burnt areas (*U* test, $P < 0.1$). Values for plots on unburnt areas were both below those for all other plots. Due to the quantities of ash generated by intense fires, plots on high intensity burn areas recorded significantly higher amounts of organic matter transfer (*U* test, $P < 0.03$) than plots on moderately burnt areas. In contrast, leaf litter amounts were significantly higher (*U* test, $P < 0.03$) on moderately burnt than intensely burnt areas. Between-plot variability in the absence of fire could not be determined due to an insufficient number of low intensity burn plots.

Factors contributing to between-plot variability include small-scale variation in fire intensities (both within and upslope of plots), localized differences in rainfall amount and intensity, spatially non-uniform activity of mound-building ants which contribute to provision of transportable sediment, and inevitable minor differences in micro-topography, vegetation regrowth, post-fire debris, and formation and destruction of litter dams within individual plots. Some of these factors also affected temporal variability in sediment and organic matter movement.

The relative differences in post-fire sediment responses on areas subjected to high, moderate or low fire intensities suggested that fire intensity in forested areas may be a useful indicator of relative movement of post-fire sediment, organic matter and leaf litter, and that frequent high intensity burns would accelerate landscape change. In grasslands the effects of varying fire intensities on post-fire sediment movement may be less pronounced, as noted by Prosser (1990).

Erskine & Melville (1983) described temporary on-slope storage of sediment and burnt vegetation in micro-terraces and litter dams in the Sydney region sandstone landscapes. Burnt organic material may therefore progress only intermittently from upper to lower slope positions, and eventually to channels. On the intensely burnt plots, similar amounts of organic matter movement were being recorded at two months and six months into the study period and these levels were consistently higher than for other plots. Fire-affected organics will thus continue to enter channel sediment for some time following fires. Once delivered to a channel, some sediment and burnt vegetation may be retained in in-channel bench or flood plain deposits.

CONCLUSION

Fire intensity in the Blue Mountains contributed to spatial variability in post-fire movement of sediment, organic matter and leaf litter. Although average sediment transfer for plots on intensely burnt areas far exceeded those for moderately burnt or unburnt areas, between-plot variability was high. Significantly greater amounts of organic matter, mainly ash, were collected on high intensity burn areas, with leaf litter amounts being highest on moderately burnt areas characterized by post-fire leaf-fall from singed canopies.

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