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Using tracer based sediment budgets to assess redistribution of soil and organic material after severe bush fires

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Abstract In the summer of 2001, a combination of severe wildfires and moderate intensity rainfall events swept through the catchment of Lake Burragorang, NSW, Australia. Beryllium-7 and $^{210}Pb_{ex}$ budgets were used to assess the redistribution of soil and organic debris that occurred on hillslopes in this catchment after the wildfire. In the ~90-ha study site, the budgets showed substantial losses of ^{7}Be from the upper plateau (10 ± 2%) and side slopes (26 ± 5%), and deposition on the lower footslopes and alluvial fans (2 ± 4%). Overall, it was possible to account for ~65% of the initial amount of ^{7}Be expected to be present with the balance, 35 ± 6%, presumably being exported offsite. Construction of a $^{210}Pb_{ex}$ budget showed a similar pattern of internal redistribution; some 28 ± 6 % of the total amount was exported from the site. Analysis of litter, soil and sediment samples shows that both ^{7}Be and $^{210}Pb_{ex}$ were: (a) preferentially retained near the soil surface (due to their constant deposition in rainfall), and (b) exhibited an affinity with organic material. It appears that ^{210}Pb and ^{7}Be budgets can reveal much about the redistribution of soil, organic (and nutrient) material after fires in these systems.

Key words bushfires; downstream impacts; fallout radionuclides; organic matter; sediment budgets; soil redistribution

INTRODUCTION

In forested catchments subject to bushfire, overland flow and soil erosion tend to increase relative to unburned forested landscapes (e.g. Swanson, 1981; Robichaud *et al.*, 2000). The effects of major bushfires on hillslope erosion processes can impact on downstream water bodies by smothering habitats with eroded sediment and by increasing their nutrient load through delivery of ash and surface litter. The magnitude of the impact varies according to the severity and areal extent of the fires, and the intensity and frequency of subsequent rainfall.

The occurrence of both severe bushfires around Sydney during December 2001, and a series of moderate post-fire rainfall events, provided an opportunity to investigate fire-induced hydrogeomorphic changes. Soil eroded from hillslopes in

Nattai National Park in the Blue Mountains, was carried downstream to Lake Burragorang, the Sydney Catchment Authority (SCA) reservoir. This permitted an investigation of the highly episodic, but almost certainly very important role of fires in the transfer of both sediment and accompanying nutrients from catchment slopes to the reservoir.

STUDY AREA

The study site is located in the Nattai National Park, approximately 100 km southwest of Sydney. The site is forested dissected plateau terrain, typical of the lower Blue Mountains. The Hawkesbury Sandstone (Triassic) forms the upper slopes and plateau surfaces, whereas the Narrabeen Group sediments form the mid to low slopes. The climate is humid temperate, with moist summers and cool winters; there is no marked dry season (Shakesby *et al.*, 2003). Following the severe bushfires during the summer of 2001–2002, a site within the Blue Gum Creek catchment was selected for the present study (see Blake *et al.*, 2005). The selected site for the present study is an ~89-ha catchment on the western side of Blue Gum Creek.

APPLICATION OF ^{210}Pb$_{ex}$ and ^{7}Be TO GEOMORPHIC STUDIES

The use of ^{7}Be and ^{210}Pb$_{ex}$ isotopes to construct sediment budgets builds on earlier work, based on such tracers as ^{137}Cs, that have provided a powerful framework for soil redistribution studies. For example, Ritchie *et al.* (1974) first constructed a coarse budget using ^{137}Cs for a forest, grass, and grass/crop watershed. The method was subsequently applied to a variety of other locations and geomorphic problems (Walling *et al.*, 1986; Quine *et al.*, 1994; Owens *et al.*, 1997). More recently, Wallbrink *et al.* (2002) used ^{137}Cs as the basis for a sediment budget constructed to assess the impact of harvesting on soil redistribution in a dry sclerophyll forest in NSW, Australia.

A similar approach can be undertaken using fallout ^{210}Pb$_{ex}$ (half life, 20.2 years), although interpretation is more complex because of this tracer's constant atmospheric input and strong affinity for organics (Koide *et al.*, 1972). It has been successfully used to trace soil and organic redistribution in a harvested forest in NSW, Australia (Wallbrink *et al.*, 1997).

Beryllium-7 is a cosmogenic nuclide with a short half-life of 53 days. Its penetration into soils tends to be shallow, declining exponentially with depth, and is generally contained within the top 20 mm of the profile (Wallbrink & Murray, 1996). This nuclide has also been used as the basis for a sediment budget for a cultivated field in the UK, where redistribution of the surface soil was determined after a single large rainfall event (Blake *et al.*, 2003). This tracer adds a short-term dynamic component to sediment budget estimates, complementing the longer term analysis provided by ^{210}Pb$_{ex}$.

Radionuclide tracers allow quantification of material fluxes by permitting construction of sediment budgets at different spatial and temporal scales. This paper documents the construction of two tracer-based (^{210}Pb and ^{7}Be) budgets. The primary aim was to investigate the rates and amounts of soil/sediment transfers (and attached nutrients) between different components of the study catchment, as well as quantifying offsite losses, during the first four months after a bushfire. A secondary aim was to use the tracers towards a more general understanding of the impact of bushfires on hillslope processes, and the potential offsite impacts on downstream impoundments.

METHODS AND EXPERIMENTAL DESIGN FOR CONSTRUCTING TRACER BUDGETS

The budget approach is based on the total amount of each tracer contained within the overall study area, and within each of its constituent landscape elements. *Reference* (*background*) *samples* from unburned areas are used to represent tracer activities in the catchment if no bushfires had occurred; whereas *slope samples* represent post-fire tracer activities, and are used to construct subsequent soil/sediment budgets. The sum of the tracer amounts within each of the landscape elements from the slope samples should match the overall amount estimated from the reference samples, if no net losses from the system have occurred. Thus, overall losses occur as deficits in the total amount of the tracer in the budget. Analysis of the tracer amounts within individual landscape elements will indicate where this loss is likely to have occurred, as well as providing information on the flow of material within and between elements. For a more complete description of the development and use of this method in forested areas see Wallbrink *et al.* (2002).

To construct fallout radionuclide budgets, the following are required: (a) the surface area of each landscape element (m^2); (b) the activities of $^{210}Pb_{ex}$ and ^{7}Be within each of these elements (Bq kg^{-1}); and (c) a reference activity for each radionuclide from an unburned slope with similar characteristics to those of the severely burned areas.

The study area was divided into five landscape units: (a) ridgetop and plateau; (b) sideslopes (angles >11°); (c) a pre-existing mound; (d) lower (riparian) slope; and (e) a clearly identifiable outwash fan. The ridgetop and sideslope units were delineated on the basis of slope angle (above or below 11°). Their specific areas were calculated from GIS analyses of aerial photographs. The “pre-existing fan” appears to be a relict feature of late Pleistocene age (Tomkins *et al.*, 2004) which, along with the recent outwash fan, was assessed on the ground using a closed line survey. The lower slope/riparian unit occupied the remaining areas of the catchment.

Soil cores used to determine the tracer activities for each landscape element were obtained by hand augering at depth increments of 0–2, 2–5 and 5–30 cm; their surface areas were 0.00785 m^2 for the 0–2 cm and 2–5 cm, and 0.00581 m^2, respectively. Sampling was undertaken along three transects per landscape element, with cores taken at 2 m intervals along each transect (a total of 45 cores). “Reference” area $^{210}Pb_{ex}$ and ^{137}Cs activities were obtained from 20 individual cores taken at ~1 km intervals along a nearby ridge aligned perpendicular to the study site, and from a neighbouring paddock for ^{7}Be. These cores were also obtained by means of hand augering using the same depth increments as described above, based on assumptions outlined in Quine *et al*. (1994) regarding reference site suitability.

A series of soil/sediment samples were also taken to investigate the partitioning of $^{210}Pb_{ex}$ and ^{7}Be with respect to organic content and particle size. A complete description of the procedures for analysing these samples is given in Shakesby *et al.*

(2003). All soil samples were analysed for field moisture content, bulk density and loss on ignition (LOI). The samples were then cast in a polyester resin matrix and analysed by gamma spectrometry at the CSIRO radionuclide laboratories in Canberra, Australia, according to the methods of Murray *et al.* (1987).

RESULTS

The specific activities (Bq kg^{-1}), areal activities (Bq m^{-2}), total amounts (MBq), and reference values are given in Tables 1, 2 and 3 for $^{210}Pb_{ex}$, ^{7}Be, and ^{137}Cs, respectively, for each landscape element. The total amounts of each nuclide (in MBq) expected in each element before the fire are derived by multiplying the reference value (Bq m^{-2}) by the area of the element (m^2). The total amount after the fire (MBq) is calculated by multiplying the measured inventory (Bq m^{-2}) by the area of each element (m^2). The difference is calculated by subtracting the two values from one another. These data can also be expressed graphically (e.g. Fig. 1 for $^{210}Pb_{ex}$) to describe the redistribution of nuclides within and between the various landscape elements of the study area. This is undertaken by calculating the relative proportions of the pre and post total amounts (MBq)—for each nuclide in each landscape element—to the total initial amount in the catchment (in MBq), which in turn is then normalized to 100%. The $^{210}Pb_{ex}$ and ^{7}Be budgets both suggest that there have been some losses from the plateau area, although the most significant losses have occurred from the sideslope regions (Tables 1 and 2; Fig. 1). Indeed, losses from this landscape element account for the majority of the overall tracer losses from the system [28 ± 4% ($^{210}Pb_{ex}$) and 35 ± 5% (^{7}Be)]. However, these losses were not reflected in a corresponding ^{137}Cs budget which only showed a negligible difference (4 ± 1%); in fact, the overall losses of ^{137}Cs were small compared to both $^{210}Pb_{ex}$ and ^{7}Be. Although there appear to have been minor gains and losses, as

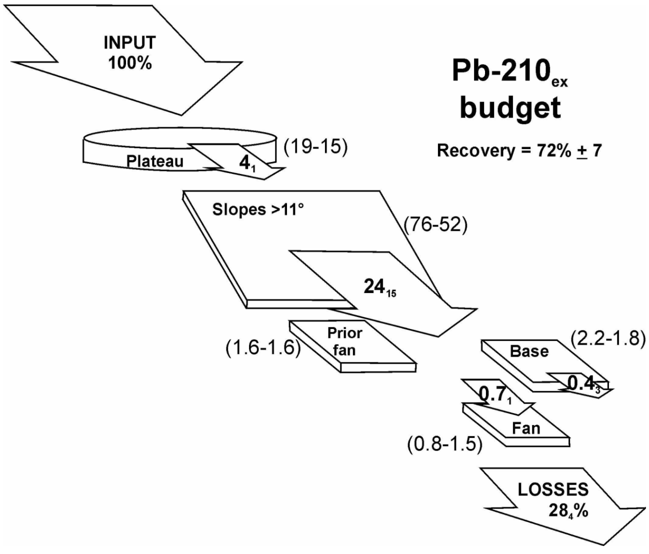

Fig. 1 A radionuclide based budget for $^{210}Pb_{ex}$ for the study area following a severe bushfire and moderate rainfall. Values within the arrows represent tracer amounts either transported from or deposited within each element, as a fraction of the total initial input. Values in parentheses represent the amount of activity contained within each element before and after the bushfire, as a percent of total inputs.

Table 1 Tracer budget for ^{210}Pb$_{ex}$ for landscape elements within the Nattai study area.

Lead–210	Area		Inventory (after fire)		Before fire		After fire		Diff.		% change
	(m^2)	(%)	(Bqm^2)	se	(MBq)	se	(MBq)	se	(MBq)	se	
Plateau (< 11°)	172102	19.3	1482	38	331	9	255	7	–75.9	10.8	–22.9
Slopes (> 11°)	679371	76.1	1309	45	1307	45	889	30	–417.3	54.0	–31.9
Pre–existing fan	13934	1.6	1915	113	27	2	27	2	–0.1	2.2	–0.4
Base	19967	2.2	1588	163	38	4	32	3	–6.7	5.1	–17.4
New fan	7063	0.8	3565	105	14	0	25	1	11.6	0.8	85.4
Reference			1923	171							
Totals	892437	100.0			1716.3	153	1227.9	31.3	–488.4	158	–28.5

se = standard error.

Table 2 Tracer budget for ^{7}Be for landscape elements within the Nattai study area.

Beryllium–7	Area		Inventory (after fire)		Before fire		After fire		Diff.		% change
	(m^2)	(%)	(Bqm^2)	se	(MBq)	se	(MBq)	se	(MBq)	se	
Plateau (< 11°)	172102	19.3	128.5	39.2	45.7	14	22.1	6.8	–23.6	15.5	–51.6
Slopes (> 11°)	679371	76.1	175.3	33.7	180.4	34	119.1	22.9	–61.4	41.6	–34.0
Pre–existing fan	13934	1.6	170.9	48.1	3.7	1.0	2.4	0.7	–1.3	1.2	–35.7
Base	19967	2.2	399.9	31.6	5.3	0.4	8.0	0.6	2.7	0.8	50.6
New fan	7063	0.8	324.1	13.3	1.9	0.1	2.3	0.1	0.4	0.1	22.0
Reference			265.6	14.8							
Totals	892437	100.0			237.0	13	153.9	23.9	–83.2	27.3	–35.1

se = standard error.

Table 3 Tracer budget for ^{137}Cs for landscape elements within the Nattai study area.

Caesium–137	Area		Inventory (after fire)		Before fire		After fire		Diff.		% change
	(m^2)	(%)	(Bqm^2)	se	(MBq)	se	(MBq)	se	(MBq)	se	
Plateau (< 11°)	172102	19.3	398	10	85	2	69	2	–16.4	2.7	–19.3
Slopes (> 11°)	679371	76.1	491	9	335	6	334	6	–1.6	8.4	–0.5
Pre–existing fan	13934	1.6	444	13	7	0	6	0	–0.7	0.3	–10.0
Base	19967	2.2	367	17	10	0	7	0	–2.5	0.6	–25.6
New fan	7063	0.8	988	11	3	0	7	0	3.5	0.1	100.2
Reference			493	34							
Totals	892437	100.0			440.4	30.1	422.7	6.2	–17.7	30.8	–4.0

se = standard error.

well as redistributions within the lower-lying landscape elements, all three tracers showed losses from the plateau landscape element.

The activities of ^{210}Pb$_{ex}$ and ^{7}Be indicate a strong affinity between these radionuclides and organic material, especially for grain sizes >63 µm. This had been noted previously in forest soils where up to 80% of ^{7}Be inventories can be associated with the overlying forest litter (Wallbrink & Murray, 1996).

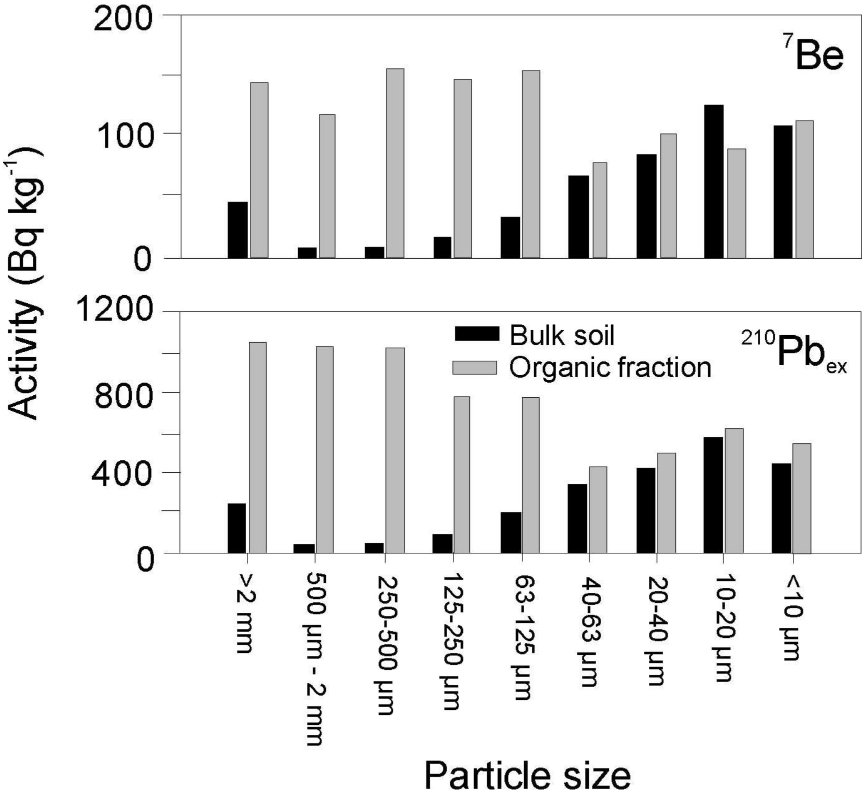

Fig. 2 $^{210}Pb_{ex}$ and ^{7}Be activities on particle size separates from bulk materials, and organic particles separated from them; note the high activities associated with the >63-µm organic fractions.

DISCUSSION

The ^{7}Be budget (with a half life of 53 days) implies that a significant redistribution of material has occurred from the sideslopes and plateau areas of the study catchment within the 4-month period after the major fire occurred. This view is also supported by the $^{210}Pb_{ex}$ budget, which shows a similar (though slightly reduced) redistribution from the plateau and sideslope regions. However, the significant losses from the latter are not supported by the ^{137}Cs data; this may imply that losses over the longer term (since 1960) were probably negligible. The differences between these results are thought to be due to two main factors:

(a) A greater amount of $^{210}Pb_{ex}$ and ^{7}Be, relative to ^{137}Cs, is associated with surface organic/litter. This appears due to the constant deposition of the first two radionuclides relative to the latter, as well as their greater affinity for organic material. Thus, the burning of the surface organic/litter in the study area may have preferentially removed a substantial amount of the $^{210}Pb_{ex}$ and ^{7}Be inventory, with subsequent offsite transport of the ash in post-fire runoff, and/or:

(b) Both $^{210}Pb_{ex}$ and ^{7}Be display maximum activity at the soil surface and are limited to shallow depth penetration, whereas ^{137}Cs is found at relatively greater depths in the mineral soil profile. Thus, any loss of surface soil removes proportionally more $^{210}Pb_{ex}$ and ^{7}Be than ^{137}Cs. Hence, losses of ^{137}Cs are only expected if erosion involves deeper soil layers.

These results imply that the $^{210}Pb_{ex}$ and ^{7}Be data most likely represent organic/ash material lost from the system shortly after the bushfire, whereas the ^{137}Cs data indicate very low rates of mineral soil relocation. The presumption regarding limited displacement of mineral soil after the December 2001 bushfire is supported by actual measurements of soil movement (Shakesby *et al.*, 2003). The rapid remobilization of organic/ash, together with silt/clay, after a fire and as a result of moderate rainfall events, indicates the potential for extensive nutrient redistribution within the catchment, and for substantial post-fire impacts on downstream impoundments.

CONCLUSIONS

The following preliminary conclusions can be drawn from this study:

(a) There is significant short-term soil/sediment/ash redistribution on slopes resulting from major bushfires.
(b) Sediment mobilization occurs mainly in conjunction with burned organic material/ash derived from the sideslope areas of the study catchment.
(c) The overall losses of ^{7}Be and $^{210}Pb_{ex}$ indicate the potential for significant transfer of organic matter/nutrients to offsite areas.
(d) The ^{137}Cs budget suggests that longer-term slope losses of mineral soil may be minimal.

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