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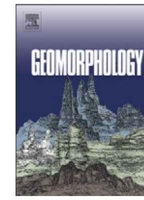

Quantifying sources of fine sediment supplied to post-fire debris flows using fallout radionuclide tracers

Hugh G. Smith [a,b,*], Gary J. Sheridan [b], Petter Nyman [b], David P. Child [c], Patrick N.J. Lane [b], Michael A.C. Hotchkis [c], Geraldine E. Jacobsen [c]

[a] *School of Geography, Earth and Environmental Sciences, University of Plymouth, Devon, PL4 8AA, UK*
[b] *Department of Forest and Ecosystem Science, The University of Melbourne, Victoria, 3010, Australia*
[c] *Institute for Environmental Research, Australian Nuclear Science and Technology Organisation, Lucas Heights, New South Wales, 2234, Australia*

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A B S T R A C T

Fine sediment supply has been identified as an important factor contributing to the initiation of runoff-generated debris flows after fire. However, despite the significance of fines for post-fire debris flow generation, no investigations have sought to quantify sources of this material in debris flow affected catchments. In this study, we employ fallout radionuclides (^{137}Cs, $^{210}Pb_{ex}$ and $^{239,240}Pu$) as tracers to measure proportional contributions of fine sediment (<10 μm) from hillslope surface and channel bank sources to levee and terminal fan deposits formed by post-fire debris flows in two forest catchments in southeastern Australia. While ^{137}Cs and $^{210}Pb_{ex}$ have been widely used in sediment tracing studies, application of Pu as a tracer represents a recent development and was limited to only one catchment. The ranges in estimated proportional hillslope surface contributions of fine sediment to individual debris flow deposits in each catchment were 22–69% and 32–74%. The greater susceptibility of $^{210}Pb_{ex}$ to apparent reductions in the ash content of channel deposits relative to hillslope sources resulted in its exclusion from the final analysis. No systematic change in the proportional source contributions to debris flow deposits was observed with distance downstream from channel initiation points. Instead, spatial variability in source contributions was largely influenced by the pattern of debris flow surges forming the deposits. Linking the tracing analysis with interpretation of depositional evidence allowed reconstruction of temporal sequences in sediment source contributions to debris flow surges. Hillslope source inputs dominated most elevated channel deposits such as marginal levees that were formed under peak flow conditions. This indicated the importance of hillslope runoff and fine sediment supply for debris flow generation in both catchments. In contrast, material stored within channels that was deposited during subsequent surges was predominantly channel-derived. The results demonstrate that fallout radionuclide tracers may provide unique information on changing source contributions of fine sediment during debris flow events.

1. Introduction

Debris flows can occur following wildfire in steep forest environments and result in severe erosion and downstream sediment redistribution (Wohl and Pearthree, 1991; Meyer and Wells, 1997; Cannon, 2001). Post-fire debris flows may be characterised according to their primary initiation mechanism. Elevated surface runoff from recently burned hillslopes may progressively entrain material until debris flow conditions are reached either on hillslopes or within channels (Cannon et al., 2001a, 2001b; Gabet and Bookter, 2008). In contrast, soil saturation and loss of tree root cohesive strength after fire may result in shallow landslides that deliver large quantities of material downstream as a debris flow (Swanson, 1981; Benda and Dunne, 1997; Meyer et al., 2001; Wondzell and King, 2003). In some instances post-fire debris flows may be generated by a combination of these processes (Cannon and Gartner, 2005). Debris flows can scour channels to bedrock and form extensive coarse material deposits behind log-jams and along channel sections with reduced gradients (Meyer and Wells, 1997; Santi et al., 2008). Coarse terminal fan deposits may form at stream junctions causing flow redirection and channel adjustments in trunk streams (May and Gresswell, 2004). Substantial quantities of fine sediment and ash may also be delivered to streams and impact on water quality (Smith et al., 2011a).

Previous research on post-fire debris flows has been largely concentrated in the western United States and Canada, while the occurrence of debris flows following fire has also been reported in the Swiss Alps (Conedera et al., 2003) and in the forested uplands of southeastern Australia (Nyman et al., 2011). In North America,

* Corresponding author at: School of Geography, Earth and Environmental Sciences, University of Plymouth, Devon, PL4 8AA, UK. Tel.: +44 1752 584985.
E-mail address: hugh.smith@plymouth.ac.uk (H.G. Smith).

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investigations of post-fire debris flow occurrence initially focused on documenting events, with particular attention on debris flow generation processes as well as analysis and interpretation of past debris flow deposits (Wells, 1987; Wohl and Pearthree, 1991; Spittler, 1995; Meyer and Wells, 1997; Cannon et al., 1998; Cannon and Reneau, 2000; Cannon, 2001; Cannon et al., 2001a; Meyer et al., 2001; VanDine et al., 2005). Subsequently, researchers have sought to quantify storm rainfall conditions and thresholds responsible for generating post-fire debris flows (Cannon et al., 2008) and develop empirical models relating the volume of material eroded to various landscape attributes as well as rainfall characteristics (Gabet and Bookter, 2008; Gartner et al., 2008; Cannon et al., 2010). The frequency of post-fire debris flows and their contribution to long-term erosion have also been the subject of both field and modelling based investigations (Meyer et al., 1992; Benda and Dunne, 1997; Istanbulluoglu et al., 2004; Pierce et al., 2004).

Progressive sediment entrainment by surface runoff has been identified as the dominant initiation process of most post-fire debris flows studied in the western United States (Cannon and Gartner, 2005). Likewise, in southeastern Australia, Nyman et al. (2011) reported the occurrence of multiple runoff-generated debris flows after fire in steep headwater catchments under dry eucalypt forest burned at high severity. Sources of material transported by runoff-generated debris flows have received some attention. Santi et al. (2008) presented an analysis of sources based on a survey of 46 debris flows in the western United States and found that channel erosion was the dominant source of material with rills making only a minor contribution (0.1–10.5%). Interrill erosion was not measured in this study. Nyman et al. (2011) measured both hillslope and channel erosion across three catchments affected by post-fire debris flows in southeastern Australia and found that hillslopes contributed 25–65% of the total estimated mass of eroded material.

The previous studies reporting sources of post-fire debris flow material are based on volumetric surveys that include the complete range of particle size fractions. However, quantifying hillslope and channel source contributions of fine sediment (clay and silt) to debris flows may also provide valuable insights. The supply of fine sediment and ash has been identified as an important factor contributing to the process of progressive sediment entrainment that is associated with the initiation of runoff-generated debris flows after fire (Meyer and Wells, 1997; Cannon et al., 2001b; Gabet and Sternberg, 2008; Gabet and Bookter, 2011). More generally, fine sediment is important for producing debris flow conditions through its contribution to shear strength via cohesion in clays and inter-particle friction (Costa, 1988). Therefore, identification of the sources of fine sediment transported by debris flows can offer a means to better understand debris flow generation after fire. Furthermore, reconstructing temporal sequences of source contributions to debris flows may be possible by combining knowledge of source inputs to individual debris flow deposits with analysis of the spatial arrangement of deposits within channels.

Sources of fine sediment transported by post-fire debris flows may be quantified using fallout radionuclides as sediment tracers. Caesium-137 (^{137}Cs) and excess lead-210 (^{210}Pb$_{ex}$) have been widely applied as tracers to determine the relative hillslope surface and channel bank source contributions to sediment stored and transported in river networks (e.g. Wallbrink et al., 1998, 2003; Walling et al., 1999, 2008; Russell et al., 2001; Collins and Walling, 2002; Whiting et al., 2005; Smith and Dragovich, 2008). Recently, plutonium-239 and 240 (^{239,240}Pu) have been investigated as potential sediment tracers, with ^{239}Pu successfully employed to trace sediment sources in a river basin in Queensland, Australia (Everett et al., 2008; Tims et al., 2010). We propose to use ^{137}Cs, ^{210}Pb$_{ex}$ and ^{239,240}Pu as tracers to quantify the proportional contributions of fine sediment from hillslope surface and channel bank sources to material stored in channel deposits formed by debris flows. The study focuses on two small forest catchments that experienced runoff-generated debris flows following wildfires in southeastern Australia. While there has been limited application of fallout radionuclides to trace sediment sources in catchments after wildfire (Blake et al., 2009; Wilkinson et al., 2009; Smith et al., 2011b), the present study represents the first application of these tracers to investigate fine sediment sources of post-fire debris flows. In addition to the sediment tracing analysis, we also date past debris flow deposits found in one of the catchments. This leads to consideration of the possible contribution made by such high magnitude erosion events after fire to long-term erosion and soil profile change based on available data from the region.

2. Study area

The study sites are located in the forested uplands of central and northeastern Victoria, Australia (Fig. 1a). Sampling focused on two small catchments situated within Myrtle and Sunday Creeks, which are located in the Goulburn and Ovens River basins, respectively. The study sites were included in a catalogue of high magnitude erosion events that occurred after wildfire in the eastern uplands of Victoria and were classified as runoff-generated debris flows on the basis of field evidence of debris flow processes (Nyman et al., 2011). This evidence included the presence of unsorted levee deposits along channel margins, matrix filling of voids between large clasts within deposits, severe channel scour, damage to vegetation, the presence of levee-lined rills on hillslopes, and the absence of soil slips within hillslope initiation zones (Costa, 1988; Hungr et al., 2001; Pierson,

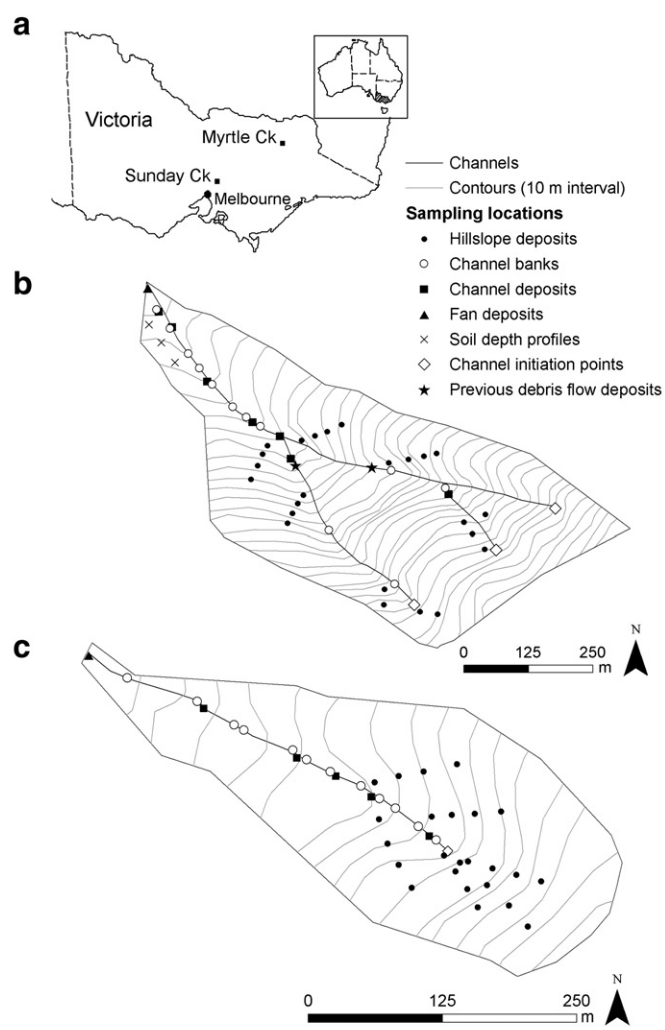

Fig. 1. Location of the two debris flow-affected study catchments in (a) Victoria, Australia, and catchment maps with sampling locations for the (b) Myrtle Creek and (c) Sunday Creek study sites.