Geomorphology 250 (2015) 173–186

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Predicting sediment delivery from debris flows after wildfire

Petter Nyman [a,b,*], Hugh G. Smith [c], Christopher B. Sherwin [a,b], Christoph Langhans [a], Patrick N.J. Lane [a], Gary J. Sheridan [a,b]

[a] School of Ecosystems and Forest Sciences, University of Melbourne, Carlton, Victoria 3010, Australia
[b] Bushfire Cooperative Research Centre, 340 Albert Street, East Melbourne, Victoria 3002, Australia
[c] School of Environmental Sciences, University of Liverpool, L69 7ZT, UK

ARTICLE INFO

Article history:
Received 23 April 2015
Received in revised form 29 August 2015
Accepted 31 August 2015
Available online 5 September 2015

Keywords:
Debris flow
Wildfire
Erosion
Sediment yield

ABSTRACT

Debris flows are an important erosion process in wildfire-prone landscapes. Predicting their frequency and magnitude can therefore be critical for quantifying risk to infrastructure, people and water resources. However, the factors contributing to the frequency and magnitude of events remain poorly understood, particularly in regions outside western USA. Against this background, the objectives of this study were to i) quantify sediment yields from post-fire debris flows in southeast Australian highlands and ii) model the effects of landscape attributes on debris flow susceptibility. Sediment yields from post-fire debris flows (113–294 t ha^{-1}) are 2–3 orders of magnitude higher than annual background erosion rates from undisturbed forests. Debris flow volumes ranged from 539 to 33,040 m^3 with hillslope contributions of 18–62%. The distribution of erosion and deposition above the fan were related to a stream power index, which could be used to model changes in yield along the drainage network. Debris flow susceptibility was quantified with a logistic regression and an inventory of 315 debris flow fans deposited in the first year after two large wildfires (total burned area = 2919 km^2). The differenced normalised burn ratio (*dNBR* or burn severity), local slope, radiative index of dryness (*AI*) and rainfall intensity (from rainfall radar) were significant predictors in a susceptibility model, which produced excellent results in terms identifying channels that were eroded by debris flows (Area Under Curve, *AUC* = 0.91). Burn severity was the strongest predictor in the model (*AUC* = 0.87 when *dNBR* is used as single predictor) suggesting that fire regimes are an important control on sediment delivery from these forests. The analysis showed a positive effect of *AI* on debris flow probability in landscapes where differences in moisture regimes due to climate are associated with large variation in soil hydraulic properties. Overall, the results from this study based in the southeast Australian highlands provide a novel basis upon which to model sediment delivery from post-fire debris flows. The modelling approach has wider relevance to post-fire debris flow prediction both from risk management and landscape evolution perspectives.

1. Introduction

Debris flows after fire can be a major process by which sediment erodes from hillslopes and headwaters (Wohl and Pearthree, 1991; Meyer et al., 2001; Cannon et al., 2003; Gabet and Bookter, 2008; Kean et al., 2011; Nyman et al., 2011; García-Ruiz et al., 2013; Jordan, 2015). Their frequency and magnitude are therefore important for landscape evolution and sediment availability in upland rivers and streams (Rutherfurd et al., 1994; Gomi et al., 2002; Benda et al., 2003; Miller et al., 2003). Debris flows can also pose a considerable threat to water supply systems (White et al., 2006; Smith et al., 2011a) and other assets (Cannon and Gartner, 2005; Lyon and O'Connor, 2008). Models for predicting sediment delivery and hazards from post-fire debris flows are therefore needed. Currently the major limitation in the development of such models is the lack of fundamental data on event magnitude and the susceptibility of different landscapes to erosion by debris flows. Lack of data also means that the longer-term implications of these high magnitude events remain poorly understood.

Wildfire-related debris flows can be triggered by slope failure due to reduced root cohesion (Benda and Dunne, 1997; Wondzell and King, 2003) or they can be runoff-generated and triggered by overland flow and sediment bulking (Meyer and Wells, 1997; Cannon et al., 2003). Wildfire contributes to runoff-generated (or progressively bulked) debris flows by reducing infiltration and increasing sediment availability on hillslopes (Wells, 1987; Cannon et al., 2001a; Gabet and Sternberg, 2008; Nyman et al., 2013, 2014a). The processes causing runoff-generated debris flows include a combination of i) runoff production (Cannon et al., 2001a; Kean et al., 2011), ii) rill erosion (Cannon et al., 2001a), iii) thin hillslope failures (Gabet, 2003) and iv) channel incision in converging zero-order headwaters (Cannon et al., 2001b; Gabet and

* Corresponding author at: School of Ecosystems and Forest Sciences, University of Melbourne, Carlton, Victoria 3010, Australia.
E-mail address: nymanp@unimelb.edu.au (P. Nyman).

http://dx.doi.org/10.1016/j.geomorph.2015.08.023
0169-555X/

Bookter, 2008). The persistence of debris flow processes in downstream channels depends on local slope and channel configuration as well as changes in flow rheology due to runoff accumulation, sediment entrainment and deposition within channels (Iverson, 1997; Cannon et al., 2003; Pelletier and Orem, 2014; Kean et al., 2013; Staley et al., 2014; Gartner et al., 2015).

Attributes related to infiltration are an important source of variation in debris flow susceptibility in burned areas (Wells, 1987; Cannon et al., 2001b; Jordan et al., 2004; Nyman et al., 2011). Infiltration is affected by burn severity (Moody et al., 2015) but can also vary with intrinsic catchment attributes related to climate, vegetation and soils in the burned area (Jenny, 1994; Wondzell and King, 2003; Nyman et al., 2014a). Aridity (or the balance between net radiation and precipitation) in particular is emerging as an important source of variation in hillslope processes at the local and regional scales (Wondzell and King, 2003; Ebel, 2013; Sheridan et al., 2015). After a fire the runoff response will also depend on the intensity and duration of rainfall (Cannon et al., 2011; Kean et al., 2012; Staley et al., 2012), which can be spatially variable during the vulnerable post-fire period. The role of burn severity, intrinsic landscape attributes, and rainfall patterns in controlling runoff production and debris flow response from burned areas is further complicated by variation in the scale (or drainage area) within which the debris flow processes operate. In low relief terrain for instance, the debris flows are confined to relatively small drainage areas with terminal deposits located in 1st or 2nd order drainage lines (e.g. 0.01–0.1 km^2). In high relief terrain the debris flows persist into 3rd and 4th order drainages and thus operating within a much larger spatial domain (e.g. 0.1–10 km^2).

The physical processes contributing to the initiation and propagation of runoff generated debris flows are complex and difficult to model. Using a mechanistic modelling approach Kean et al. (2013) showed that the initiation, frequency and magnitude of debris flow surges are regulated by channel slope with low gradient sections acting as 'sediment capacitors' temporarily storing eroded sediment before its released as mass failure due to the downstream forces exceeding the resisting forces. This process is sensitive to runoff production, sediment availability, grain-size and topographic attributes. The parameters needed to model these processes are rarely available for large areas, and for practical purposes the debris flow magnitude and susceptibility are often modelled though empirical analysis of inventories (Van Den Eeckhaut et al., 2006; Blahut et al., 2010; Cannon et al., 2010). Statistical models of debris flow initiation and magnitude have been developed specifically for burned areas to help mitigate post-wildfire risks (Gartner et al., 2008, 2014; Pak and Lee, 2008; Cannon et al., 2010). These models use information on catchment attributes and rainfall to produce estimates of debris flow probability and magnitude at the catchment outlet where infrastructure, homes and people may be at risk of direct impact from the debris flow.

In southeast Australia, debris flows in burned areas were only recently recognised as an important erosion process (Nyman et al., 2011; Smith et al., 2012). The lack of data on post-fire debris flows in this region mean that their magnitude, sediment sources and the factors contributing to variability in susceptibility remain poorly understood. In this study the overall goal is therefore to collect the data needed for developing models of sediment delivery from debris flows. The study takes a landscape-scale approach towards predicting debris flow probability while seeking to explicitly represent the distribution of erosion and deposition within debris flow producing catchments. The study was designed with three main objectives:

1. Use field surveys of post-fire debris flows to quantify magnitude of erosion, the sediment sources and the triggering storm conditions
2. Analyse erosion and deposition rates with respect to slope and drainage area
3. Develop a model of debris flow susceptibility for large burned areas using data on burn severity, landscape attributes (e.g. slope and aridity) and rainfall intensity that are available at regional scales

2. Study area

The study is carried out in the eastern uplands of Victoria, southeast Australia (Fig. 1). The region forms part of the Great Dividing Range, and is described by Jenkins (1991) as a belt of "ridges, plateaus and corridors". Elevation ranges from 200 m above sea level (a.s.l.) in foothills to 2000 m a.s.l. in the alpine regions along ridges and on upland plateaus. A large majority of the bedrock is of Palaeozoic origin and consists of marine sedimentary rocks (mudstone, shales and sandstone). The sedimentary geology is interspersed by granitic intrusions and some volcanic rock. Vegetation is dominated by Eucalyptus species in open dry forests through to tall temperate rainforests. Drier regions (rainfall <1000 mm yr^{-1}) consist of mixed-eucalypt forests on gravelly and relatively shallow soils (<1 m). In higher rainfall areas (>1500 mm yr^{-1}) the vegetation shifts towards uniform stands of Mountain or Alpine Ash where soils tend to be deep (>1 m) and well structured.

The average annual precipitation ranges from 600 to 2500 mm, the majority of which is produced from cold fronts during winter and spring (May–November) when easterly moving continental high pressure systems are interspersed with easterly or north-easterly moving low pressure systems that originate in the southern ocean. When moist air masses reach the eastern uplands, the mountainous terrain and the prevailing north-easterly moving pressure systems result in strong orographic precipitation gradients. In general, precipitation increases with altitude and tends to be higher on the south and south-westerly slopes of the dividing ranges. In winter, precipitation often falls as snow at elevations greater than 1200 m a.s.l. Summer and autumn rainfall (December–April) is less frequent but often occurs as high intensity storms.

Streamflow usually peaks towards the end of winter and in spring (September–November). Large peaks in streamflow can occur during summer storms but these runoff events are relatively rare in undisturbed forests due to the dense vegetation cover and relatively high infiltration rates (Bren, 2014). In the absence of wildfire the main mechanism of sediment delivery is therefore landslides and debris flows that originate from mass failure during long-duration and high intensity rainstorms (e.g. Rutherfurd et al., 1994). The average annual maximum 15- and 30-min rainfall intensities (I_{15} and I_{30}) across the region range from 30 to 50 mm h^{-1} and 22–31 mm h^{-1}, respectively. After wildfire these rainfall intensities are often sufficient to produce large amounts of surface runoff (Bren, 2014; Smith et al., 2011b) and can result in runoff-generated debris flows when the terrain is sufficiently steep (Nyman et al., 2011). In general, there is a tendency for drier parts of the landscape to produce more surface runoff after wildfire and they are therefore more sensitive to erosion (Sheridan et al., 2015).

Between 2003 and 2009, there were three major wildfire events in the region, burning a total of nearly 30,000 km^2. Much wildfire activity during this period has been attributed to drought as well as the build-up of high fuel loads due to effective fire suppression (Cai et al., 2009; Adams, 2013). However, the magnitude of these fire events in terms of severity and extent are not unprecedented. These types of large, uncontrolled wildfires typically account for the bulk of the average annual area burned in fire-prone landscape (Reed and McKelvey, 2002). The Alpine Fires and the Great Divide Fire Complex in 2003 and 2007, respectively, both burned over several weeks resulting in patchy footprint with mixed burn severities including understorey burns as well as crown fires. The Black Saturday Wildfires in 2009 burned mostly during extreme fire weather over the course of 12 h and left large areas with a homogenous footprint where the crowns had been partially or completely combusted. This study presents data on debris flow magnitude and frequency in two of these large burned areas. Field-based erosion surveys for quantifying yield were carried in the 2007 Great Divide Fire Complex and in the 2009 Black Saturday fires. A debris flow inventory for developing a susceptibility model was collected from the 2009 Black Saturday fires.