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Characterizing the primary material sources and dominant erosional processes for post-fire debris-flow initiation in a headwater basin using multi-temporal terrestrial laser scanning data

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ABSTRACT

Wildfire dramatically alters the hydrologic response of a watershed such that even modest rainstorms can produce hazardous debris flows. Relative to shallow landslides, the primary sources of material and dominant erosional processes that contribute to post-fire debris-flow initiation are poorly constrained. Improving our understanding of how and where material is eroded from a watershed during a post-fire debris-flow requires (1) precise measurements of topographic change to calculate volumetric measurements of erosion and deposition, and (2) the identification of relevant morphometrically defined process domains to spatially constrain these measurements of erosion and deposition. In this study, we combine the morphometric analysis of a steep, small (0.01 km^2) headwater drainage basin with measurements of topographic change using high-resolution (2.5 cm) multi-temporal terrestrial laser scanning data made before and after a post-fire debris flow. The results of the morphometric analysis are used to define four process domains: hillslope-divergent, hillslope-convergent, transitional, and channelized incision. We determine that hillslope-divergent and hillslope-convergent process domains represent the primary sources of material over the period of analysis in the study basin. From these results we conclude that raindrop-impact induced erosion, ravel, surface wash, and rilling are the primary erosional processes contributing to post-fire debris-flow initiation in the small, steep headwater basin. Further work is needed to determine (1) how these results vary with increasing drainage basin size, (2) how these data might scale upward for use with coarser resolution measurements of topography, and (3) how these results change with evolving sediment supply conditions and vegetation recovery.

1. Introduction

Wildfire dramatically alters the short-term hydrological response of steep watersheds to high intensity rainstorms and increases the likelihood of flash flooding and debris flows (Cannon, 2001; Shakesby and Doerr, 2006; Cannon and DeGraff, 2009). The chaparral-dominated mountains of southern California are particularly prone to post-fire debris flows. Communities, infrastructure, and important habitats and water resources are frequently located within debris flow pathways. The proximity to debris flow pathways can lead to potential catastrophic consequences. These risks create a need to better understand the mechanisms by which post-fire debris flows initiate in order to improve our ability to predict likelihood and magnitude of the debris flow and mitigate their potential hazards. In particular, further insight is needed into how runoff from high-intensity rainfall transitions to debris flow in steep headwater basins.

In unburned settings, landslides and soil slips often initiate debris flows. In this case, a discrete slope failure mobilizes into a debris flow and travels downslope and into the drainage network (Costa, 1984; Johnson and Rodine, 1984). Infiltration during long duration rainstorms increases pore-water pressure within the soil until the material's shear strength is exceeded, and a Coulomb slope failure occurs (Innes, 1983; Costa, 1984; Reneau and Dietrich, 1987; Iverson, 2000). This type of initiation process is easily identified in the field, as the slope failure produces a discrete landslide scar often located in areas of convergent surface or subsurface flow (e.g., Reneau and Dietrich, 1987; Montgomery et al., 2009).

In recently burned areas, debris flows do not necessarily exhibit a discrete initiation point (Parrett, 1987; Meyer and Wells, 1997; Cannon, 2001). Instead, post-fire debris flows are usually generated from entrainment of material by surface water runoff distributed throughout the watershed. Meyer and Wells (1997) described this process as one of progressive bulking based on their observations of erosion features associated with a post-fire debris flow in Yellowstone National Park. They observed that large areas of shallow (~1 cm) erosion on hillslopes gradually transitioned to deeper rills (1–12 cm in depth). Farther downslope, rills graded into deep, narrow gullies incised into areas

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of convergent flow, which subsequently transitioned to stream channels that were eroded to bedrock. They concluded that increasing sediment concentration in surface runoff ultimately contributed to the transition from clear water flow into debris flow. This process has subsequently been observed in other burned areas throughout the world (Cannon and Reneau, 2001; Cannon et al., 2001a,b, 2003; Nyman et al., 2011; Smith et al., 2012).

Erosion of steeplands after wildfire is considered to be a combination of gravitational processes (raveling and rockfall), raindrop-impact-induced erosion (RIIE), surface wash, expansion of the drainage network through headward expansion of the rill and gully network, fluvial erosion, and erosion by debris flow (Cannon, 2001; Gabet, 2003a,b; Kinnell, 2005; Shakesby and Doerr, 2006; Kean et al., 2011; Lamb et al., 2011; Nyman et al., 2011; Smith et al., 2012). Despite the general consensus that erosional processes during high intensity rainfall are responsible for post-fire debris-flow initiation, disagreement exists regarding what processes are most responsible for contributing sediment to post-fire debris flow. Varying emphasis has been placed on the relative importance of raveling, hillslope erosion and erosion of material stored in channels.

Between the wildfire and the first rainstorm, processes such as raveling and aeolian transport are responsible for the transport of materials downslope and to stream channels. Post-fire raveling rates are significantly higher, as physical and chemical changes in soils tend to decrease cohesion between particles, and the combustion of vegetation releases wedges of sediment trapped behind stems and roots during wildfire (Florsheim et al., 1991; Gabet, 2003b; Shakesby and Doerr, 2006; Lamb et al., 2011). Lamb et al. (2011) concluded that post-fire raveling represents one of the primary mechanisms by which post-fire sediment yield is increased following wildfire in steep terrain. The rapid influx of material to a stream channel provides a significant source of material during subsequent runoff events, and is a primary reason for elevated debris-flow hazard in the first few years following wildfire.

Other studies have recognized the importance of both runoff-related hillslope processes and channel erosion in contributing to the initiation and magnitude of post-fire debris flows (Santi et al., 2008; Smith et al., 2012). Smith et al. (2012) analyzed the distribution of fallout radionuclides in post-fire debris-flow deposits. Their results suggested that runoff-induced erosion of fine sediment from hillslopes was the primary contributor of material for the initial surge of a post-fire debris flow. Subsequent surges were found to contain material primarily eroded from stream channels. Hillslopes were found to contribute 22–74% of the total amount of sampled fine material and represented a significant source of material in post-fire debris-flows. These findings differ from those of Santi et al. (2008), who concluded that stream channels constituted the primary source of material during post-fire debris flows. In their study, volumetric estimates of erosion were based upon sediment bulking rates. Sediment bulking rates were calculated from pre-event estimates and post-event measurements of the cross-sections of channels, gullies and rills in 46 debris-flow producing basins. The authors reported hillslopes and gullies contributed a small fraction of material to post-fire debris flows and the main channel was the primary material source. Although these studies have demonstrated that a variety of processes including ravel, rilling, and channel erosion contribute to debris-flow generation, the relative contribution of material from each process still remains largely unknown.

A major step toward improving our understanding of how post-fire debris flows initiate would be to better constrain the spatial context of the primary sources of material in post-fire debris flows. Advances in multi-temporal terrestrial laser scanning (TLS) methods allow for new means of quantifying spatial and temporal patterns of sediment transport at unprecedented spatial resolution. These data permit measurements of erosion and deposition typically constrained to point, plot, or cross-sectional scales, to be made over the entire extent of a small watershed. TLS data, when combined with geomorphic change detection methods, have proven to be a useful tool for interpreting sediment transport rates and processes in fluvial or debris-flow systems (Heritage and Hetherington, 2007; Milan et al., 2007; McCoy et al., 2010; Wheaton et al., 2010; Schurch et al., 2011; Staley et al., 2011), on landslides (Jaboyedoff et al., 2009, 2012), on hillslopes (Hancock et al., 2008), and in recently burned watersheds (Schmidt et al., 2011; Wester et al., 2014).

The spatial domains of various geomorphic processes have previously been defined through morphometric analyses of drainage basins (Evans, 1987; Dietrich et al., 1993). In particular, the form of the relation between contributing area (A_s) and local slope (S_l) has frequently been used to spatially differentiate locations where channelized processes (fluvial or debris-flow incision) are dominant from those where diffusive or hillslope processes are dominant (e.g., Beven and Kirkby, 1979; Willgoose et al., 1991; Tarboton et al., 1992; Montgomery and Foufoula-Georgiou, 1993; Montgomery and Dietrich, 1994; Willgoose, 1994; Ijjasz-Vasquez and Bras, 1995; Prosser and Abernethy, 1996; Prosser and Rustomji, 2000; Millares et al., 2012). Segregating a drainage basin into hillslope and channelized components through this type of analysis then provides a spatial context for the types of erosional processes predicted at a given location. When detailed data regarding the magnitude and spatial distribution of the erosional response during a post-fire debris flow are combined with morphometrically defined elements of the landscape, further insight will be gained into the relative importance of different types of erosional processes. These measurements may then be used to ascertain the primary sources of material and dominant erosional processes that contribute to post-fire debris-flow initiation.

In this study, high-resolution measurements of topographic changes from a debris-flow producing rainstorm are combined with the morphometric analysis of a small headwater drainage basin to: (1) quantify the spatial extent and volume of eroded material using multi-temporal TLS data, (2) segregate the watershed into spatial process domains through morphometric analysis, and (3) use the morphometrically defined process domains to make inferences regarding the primary processes that contribute to debris-flow initiation. Specifically, we use ultra-high resolution (2.5 cm) TLS data to measure the topographic changes during the analyzed rainstorm in a small, steep 0.01 km^2 headwater basin in southern California. We then differentiate, morphometrically, between hillslope-divergent, hillslope-convergent, transitional, and channel locations using traditional area–slope analysis combined with the calculation of planimetric curvature in hillslope areas. The results of the morphometric analysis compare favorably with a geomorphic map based upon repeat TLS data, therefore lending credence to the morphometrically defined process domains. We are then able to calculate the volumetric contributions from each process domain and make inferences regarding the erosional processes responsible for post-fire debris-flow initiation. In doing so, this study provides strong constraints for developing process-based models of important post-fire erosional processes, which can, in turn, lead to improved predictions of debris-flow initiation and magnitude.

2. Study area

This study analyzed a small (0.01 km^2) headwater sub-basin of the Arroyo Seco, which burned during the September 2009 Station fire (Fig. 1). This fire was the largest recorded fire in Los Angeles County history where nearly 65,000 ha of the San Gabriel Mountains were burned between 03 September and 16 October 2009. The San Gabriel Mountains are characterized by a cycle of fire followed by a period of flooding and debris flows, i.e., the “fire–flood sequence” after Hamilton et al. (1954), with a mean recurrence interval on the order of 22–37 years (Lamb et al., 2011). Post-fire erosion processes including debris flows are considered to be one of the primary drivers of long-term evolution of the San Gabriel Mountains (Lavé and Burbank, 2004).

Our study site is located on the eastern flank of Mount Lukens above La Crescenta–Montrose, CA, USA (Fig. 1A). Ninety-nine percent of our