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A morphometric analysis of gullies scoured by post-fire progressively bulked debris flows in southwest Montana, USA

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Abstract

In the fall of 2001, an intense thunderstorm in southwest Montana triggered many debris flows in the burned area of Sleeping Child Creek. In most instances, the debris flows cut deep gullies into previously unchannelized colluvial hollows and deposited large volumes of sediment onto the valley floor. The presence of rill networks above the gullies as well as the absence of landslide features indicate that the gullies were scoured by progressively bulked debris flows, a process in which dilute surface runoff becomes increasingly more laden with sediment until it transforms into a debris flow. In this contribution, we present a morphometric analysis of six of the gullies to better understand this relatively understudied process. We find that the locations of the rill heads and gully heads conform to slope-area thresholds that are characteristic of erosion by overland flow. Our data also suggest that the volumes of the debris flows increase exponentially with normalized drainage area, thus lending support to an assumption used in a recently proposed debris flow incision law. Finally, the debris flow fans have been relatively unaltered since deposition, suggesting that the valley may be currently aggrading while the hillslopes are being denuded.

Keywords: Debris flow; Fire; Natural hazard; Hyperconcentrated flow; Rocky Mountains

1. Introduction

Rates of erosion in steep landscapes typically increase dramatically after fires, with several different processes contributing to the accelerated denudation (Swanson, 1979; Wondzell and King, 2003). For example, dry ravel, the gravity-driven downslope transport of unconsolidated sediment by rolling and sliding (Wells, 1987; Gabet, 2003b; Roering and Gerber, 2005), can fill entire stream channels even before the fire has completely cooled (Florsheim et al., 1991). Burned slopes are also highly susceptible to erosion by overland flow during rainstorms, in some cases because of the creation of a hydrophobic layer that reduces the infiltration capacity of the soil and leads to greater amounts of surface runoff (DeBano, 1981). Disaggregation from the high temperatures (DeBano, 1981; Neary et al., 1999; Moody et al., 2005) and the destruction of a cohesive root mat (Cannon and Reneau, 2000) results in a loose, friable, and easily erodible soil surface. The fragility of the soil, coupled with the removal of vegetation that shields the surface from raindrop impact (Neary et al., 1999), increases the amount of sediment available for transport by overland flow, often leading to extensive sheetwash and rill erosion (Cannon and Reneau, 2000). Accelerated erosion may also occur when the upper 1–3 cm of soil becomes

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saturated above a hydrophobic layer and the pore pressures become sufficiently high to trigger a shallow landslide which mobilizes as a thin debris flow (Wells, 1987; Gabet, 2003a). The most spectacular forms of post-fire erosion, however, are the large debris flows that can excavate gullies and deliver tons of sediment over the course of a single storm (e.g., Parrett, 1987; Wells, 1987; Meyer and Wells, 1997; Cannon and Reneau, 2000; Cannon, 2001).

Debris flows can be initiated in burned landscapes through a variety of different mechanisms. First, loss of root strength from tree mortality in the years after the fire can cause shallow landslides that subsequently mobilize as debris flows (Reneau et al., 1990; Benda and Dunne, 1997b). In a second process, albeit not well documented, accumulation of dry ravel deposits in steep channels can become entrained by high discharges and form debris flows (Wells, 1987). A third process is through the progressive bulking of hillslope runoff, in which dilute flow gradually incorporates increasing amounts of sediment until it has transformed into a debris flow (e.g., Parrett, 1987; Cannon, 1997; ; Meyer and Wells, 1997; Cannon, 2001; Cannon et al., 2001). This mechanism is suggested by the presence of extensive rill networks and the absence of landslide scarps upslope of some post-wildfire debris flows (Parrett, 1987; Cannon, 1997; Meyer and Wells, 1997; Cannon, 2001; Cannon et al., 2001). It has been proposed that the availability of large quantities of fine material (i.e., vegetative ash and friable soil) characteristic of burned landscapes may be instrumental in creating these progressively bulked debris flows (Meyer and Wells, 1997; Cannon et al., 2001). Additionally, Wondzell and King (2003) observed that post-fire progressively bulked debris flows typically occur where convective storms can deliver intense bursts of rainfall.

Debris flows play a dominant geomorphic role in mountainous terrain. For example, they can deliver large pulses of sediment and wood to channels, thereby altering stream and valley morphology. The abrupt increase in sediment and large woody debris can lead to channel widening and braiding, channel aggradation, and the construction of coarse-grained terrace deposits (Benda et al., 2003a,b; Hoffman and Gabet, 2007). These changes in stream morphology due to debris flow sediment pulses can have positive and negative impacts on stream ecology. Benda et al. (2003b) found that debris flow deposits increase the physical heterogeneity of low-order stream channels. In contrast, the input of fine sediment from debris flows may cover salmonid spawning habitat (Carnefix, 2002). Over geologic time, debris flows may play a significant role in landscape evolution by controlling valley dissection in steep terrain (Stock and Dietrich, 2003; Stock and Dietrich, 2006).

Whereas debris flows by shallow landslides have been well studied (see Iverson et al., 1997 for a thorough review), debris flows generated by progressive bulking have been relatively understudied. In an effort to supplement the limited observational and quantitative data on this process, we mapped and surveyed a set of gullies scoured by progressively bulked debris flows triggered in steep, burnt terrain in the Sleeping Child Creek (SCC) basin of Montana in 2001 (Fig. 1). This site was originally documented by Cannon et al. (2003) who made a detailed map of one of the debris flow-scoured gullies and collected information on the transition from sediment-laden flow to debris flow from an additional 15 gullies. Hyde et al. (2007) also studied this site and found a positive correlation between burn severity and the spatial frequency of gullying by progressively bulked debris flows. In this contribution, we continue the geomorphic investigations at Sleeping Child Creek and present a morphometric analysis of the gullies.

2. Methods

2.1. Field site

The SCC basin is located in the Sapphire Mountains of southwest Montana, approximately 15 km south of Hamilton, Montana (Fig. 1). Over 75% of the upper SCC basin burned in the Valley Complex fires of August 2000 (Hyde, 2003). Soon after the fire, a frontal storm passed over the area on September 30–October 1; although this storm generated a 100-year flow in Sleeping Child Creek, no debris flows were triggered (Parrett et al., 2004). The following year, a convective storm on July 15 triggered at least 16 debris flows in the burned region of the SCC basin (Fig. 2A, B). The 30-minute rainfall intensity for this storm was 17 mm/h in the lower SCC basin, an intensity with a recurrence interval of 10–25 years (Parrett et al., 2004). The rainfall intensity, however, may have been greater in the burned portion of SCC, where steeper slopes may increase orographic effects (Lin et al., 2001).

The drainage area of the SCC basin is 169 km^2. The basin elevation ranges between approximately 1200 to 2250 m, with a mean elevation of 1900 m. The average annual precipitation is 37 cm/yr and is characterized by snowfall from November to February that accounts for ~35% of the total precipitation. The underlying lithology of the basin is predominantly gneiss and granite, and the soils are a sandy loam (Hyde, 2003). As documented