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Effects of vegetation disturbance by fire on channel initiation thresholds

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ABSTRACT

The disturbance or removal of vegetation by wildfire influences channel incision following intense rainfall events. Here we empirically examine relationships between the severity of vegetation disturbance and geomorphic controls on threshold conditions that lead to channel incision. We conducted post-fire field mapping and digital spatial analyses across 97 recently formed channel heads in the Rocky Mountains of Montana and Idaho, USA, to identify the relationship between remotely-sensed fire severity and vegetation disturbance and the source area and gradient conditions required for channel initiation. We found that the relationship between the size of source areas and source-area steepness was described by an inverse power function, consistent with established theory, across the range of fire severity, but that the magnitude of the slope–area relationship was significantly correlated with increasing fire severity. Further, at higher levels of fire severity, source areas above channel heads had lower slopes and somewhat larger areas. The findings suggest that the onset of channel incision defined by location of channel heads is controlled by fire severity and that the threshold for channel initiation decreases as vegetation disturbance increases. We also found that, in a subset of catchments for which LiDAR data were available, total curvature explained channel head location across the range of fire severity, with a small but significant contribution from source area steepness. Steepness remains more important at lower fire severity, however, and total curvature dominates where fire severity is most extreme. This suggests that forces of convergent flow are not fully expressed until a significant proportion of vegetation has been consumed such that flow resistance is minimized. Our findings, and the use of a continuous fire severity metric, contribute an ecohydrological and biogeomorphical template for studies of post-fire geomorphic responses and landscape evolution.

1. Introduction

Intense rainfall following wildfire often triggers gully rejuvenation in mountain landscapes, but the interactions among fire severity, landscape geometry, and the location of channel heads formed following fire are poorly understood. The term "gully rejuvenation" (GR) (Hyde et al., 2007, sensu Horton, 1945) captures the cyclical nature of gully formation and refill over time (Bull and Kirkby, 1997) driven by wildfire and other disturbance processes (Pierce et al., 2004). Debris flows resulting from gully rejuvenation can alter or threaten aquatic habitat (Gresswell, 1999), drinking water supplies, infrastructure, and human safety. Post-fire debris flows influence landform evolution (Benda et al., 2003; Roering and Gerber, 2005) and can supply the majority of sediment introduced into mountain streams (Pierce et al., 2004; Frechette and Meyer, 2009; Moody and Martin, 2009). Increases in the magnitude and frequency of extreme wildfires potentially induced by climate change in the western US (Westerling et al., 2006) also may have implications for the increased probability of post-fire gully rejuvenation.

The source area, also termed the zero-order catchment (Tsukamoto et al., 1982) is a region of elevated susceptibility to channel initiation (Sidle et al., 1985) where the typical concave form creates a zone of converging flow (Willgoose et al., 1991), focusing runoff into the catchment hollow (Fig. 1). Slope–area (S–A) and curvature–area (C–A) characteristics of source areas define primary controls on channel initiation thresholds (Stock and Dietrich, 2006; Yetemen et al., 2010). The slope and source area above channel heads often exhibit an inverse power–function relationship (Montgomery and Dietrich, 1988; Tarboton et al., 1992; Tucker and Bras, 1998):

$$S = kA^{-\theta} \quad (1)$$

where S is slope or topographic steepness, A is source area, a proxy for potential input of rainfall mass and energy, k is a coefficient that reflects soil and precipitation factors, and θ is a slope scaling exponent that reflects hillslope form, transport properties, and erosional processes (Kirkby, 1971; Montgomery, 2001). Together k and θ implicitly combine the effects of lithology, soils, climate, and vegetation on channel initiation

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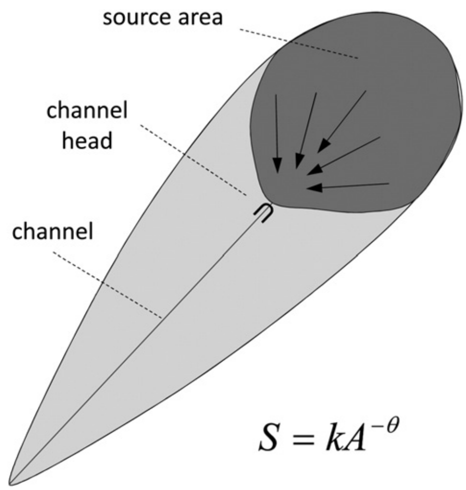

Fig. 1. Conceptual model of first-order catchment with source area, channel head location channel, converging flow paths and equation of the inverse power function relationship between source-area size (A) and slope (S).
After Willgoose et al. (1991).

processes (Yetemen et al., 2010). The correlation of area to slope varies across geographic domains (e.g. Montgomery and Dietrich, 1994; Prosser and Abernethy, 1996; Vandaele et al., 1996; Hancock and Evans, 2006) in relation to topography and other factors (Dietrich and Dunne, 1993; Vandekerckhove et al., 1998; Hancock and Evans, 2006).

Channel initiation thresholds have also been evaluated with respect to curvature (C), which quantifies topographic convexity or concavity (Zevenbergen and Thorne, 1987; Schmidt et al., 2003; Gutiérrez-Jurado and Vivoni, 2013). For example, curvature was found to strengthen the correlation of S–A relationships above ephemeral gullies in Spain and Portugal (Vandekerckhove et al., 1998); to identify channel heads in the Italian Alps (Tarolli and Dalla Fontana, 2009); and to evaluate controls on source areas above field-mapped channel heads across physiographic provinces in the eastern US (Julian et al., 2012).

Vegetation is typically not considered in analyses of slope–area relationships and channelization thresholds, despite the influence of vegetation on rainfall attenuation, surface roughness and flow resistance, and other factors affecting erosion, channel initiation, and/or gully rejuvenation (Horton, 1945; Kirkby, 1995; Hooke, 2000; Collins and Bras, 2010). Vegetation disturbance may alter driving and resisting forces on hillslopes in a manner that shifts the slope or area required for gully rejuvenation and thresholds for channelization (Dietrich et al., 1992; Lesschen et al., 2007). Drainage density, a direct expression of channel incision processes, has been associated with climate-driven vegetation types and biophysical processes (Collins and Bras, 2010). In modeling experiments, Yetemen et al. (2010) found that land surface properties related to vegetation exerted stronger controls on S–A and C–A relationships than soil properties and lithology. Runoff and erosion processes are especially sensitive to vegetation disturbance in semi-arid landscapes (Davenport et al., 1998; Wilcox et al., 2003; Allen, 2007).

Fire is an important driver of vegetation disturbance and subsequent landscape destabilization. Wildfires create burn mosaics composed of variable degrees of biomass consumption and vegetation loss (Kutiel et al., 1995) and the term fire severity refers to the degree of vegetation loss from wildfire (Keeley, 2009). Studies of S–A relationships for areas burned by wildfire have evaluated the effect of lithology on channel initiation thresholds (Cannon et al., 2001, 2003) and derived shear stress estimates from S–A relationships for gullies eroded following severe wildfire (Istanbulluoglu et al., 2003). Modeling of the influence of periodic disturbance by fire on landscape evolution suggests that whereas landslides from mass failure drive channel formation under vegetated conditions, concentrated runoff becomes the dominant erosion process for channel formation following complete vegetation removal by fire (Istanbulluoglu and Bras, 2005). Wildfire can change the dominant channel initiation processes from saturation-induced subsurface controls (Henkle et al., 2011) to initiation controlled by surface erosion processes (Wohl, 2013). Gabet and Bookter (2008) mapped nine of the same burned, gullied catchments surveyed in this study and found evidence within the S–A plots of channel initiation by Hortonian or infiltration-excess overland flow. Hancock and Evans (2006) inferred that lower channel initiation thresholds by S–A relationships reflect chronically reduced vegetation caused by very frequent fires, without directly quantifying fire effects. Comparison of channel heads formed following wildfire to those in similar undisturbed areas documented substantially smaller source areas in burned areas but found that steepness was not significantly different compared to unburned areas (Henkle et al., 2011; Wohl, 2013). Moody and Kinner (2006) discuss the effects of fire-induced changes in vegetation cover on hydrologic processes and suggest that curvature may be an important post-fire control over channel initiation processes, but they do not directly evaluate the effects of curvature or fire severity.

The purpose of this work was to study the relationship between fire severity and threshold conditions for channel initiation relative to S–A and C–A relationships, and to use this information to evaluate how physical vegetation disturbance by fire alters hydrologic and geomorphic processes. We hypothesize that in recently burned mountain landscapes, increasing fire severity and associated vegetation loss will affect the location of the channel head by reducing the threshold source area and steepness conditions for channel initiation. We also expect that gully rejuvenation will occur with lower source-area curvature where fire has consumed more vegetation.

2. Study areas and regional setting

We surveyed five areas in mountainous terrain of Montana and Idaho in the Northern Rocky Mountains, each of which has experienced recent post-fire gully rejuvenation (Fig. 2, Table 1). The Sleeping Child, Laird Creek and Cascade study areas experience a sub-Pacific precipitation regime, while the Rooks Creek and Warms Springs areas experience a medium-intensity, Plains regime (following the scheme of Moody and Martin, 2009). Snowmelt runoff is the primary input of the regional hydrology and isolated high-intensity, short-duration storms are common during hot, low humidity summer months. Thin, friable, and poorly developed sandy loam soils cover all study areas, though primary parent materials differ (Reed and Bush, 2005). Cretaceous sedimentary parent materials underlie the Cascade area with large extents of weathered boulders exposed near topographic divides. Cretaceous granitics are most common in Laird Creek with mid Proterozoic gneiss the dominant material in Sleeping Child. The bedrock for both Rooks Creek and Warm Springs is Paleozoic sedimentary material. Mixed conifer forests dominated by Douglas-fir (*Pseudotsuga menziesii*) populated the pre-fire landscape (USDOI Geological Survey, 2009); other species varied by study area. Wildfires burned the Sleeping Child and Laird Creek study areas in 2000. Severe erosion followed during summer 2001. The Rooks Creek and Warm Springs areas burned in 2007 and the Cascade burned area in 2008. Rainfall triggered debris flows in these areas between June and July 2009.

3. Methods

3.1. Field mapping of gully heads and rainfall characteristics

We inventoried the full population of first-order catchments in each study area (a total of 270 for this study, Table 1) and identified 97 channel heads (Fig. 3); Cascade (CS, $N = 10$), Laird Creek (LC, $N = 25$), Rooks Creek (RC, $N = 8$), Sleeping Child (SC, $N = 38$), and Warm Springs (WS, $N = 16$) (Fig. 2, Table 2). Field surveys were completed from 2001 to 2003 in SC and LC and from 2009 to 2011 in CS, RC, and WS. We mapped