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How do geomorphic effects of rainfall vary with storm type and spatial scale in a post-fire landscape?

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ABSTRACT

In post-fire landscapes, increased runoff and soil erosion can cause rapid geomorphic change. We examined how different types of rainfall events in 2013 affected hillslope-scale erosion and watershed-scale channel change in two 14–16 km^2 watersheds within the 2012 High Park Fire burn area in northern Colorado, USA. The first set of rainfall events was a sequence of 12 short, spatially variable summer convective rain storms, and the second was a >200 mm week-long storm in September. We compared rainfall characteristics, hillslope sediment yields, stream stage, and channel geometry changes from the summer storms to those from the September storm. The summer storms had a wide range of rainfall intensities, and each storm produced erosion primarily in one study watershed. The September storm rainfall had less spatial variability, covered both watersheds, and its total rainfall depth was 1.5 to 2.5 times greater than the total summer rainfall. Because rainfall intensities were highest during some summer storms, average hillslope sediment yields were higher for summer storms (6 Mg ha^{-1}) than for the September storm (3 Mg ha^{-1}). Maximum storm rainfall intensities were good predictors of hillslope sediment yield, but sediment yield correlated most strongly with total depths of rainfall exceeding 10–30 mm h^{-1} intensity thresholds. The combined summer storms produced relatively small changes in mean channel bed elevation and cross section area, with no clear pattern of incision or aggradation. In contrast, the sustained rain across the entire study area during the September storm led to extensive upstream incision and downstream aggradation. Because of different spatial coverage of storms, summer storms produced more total hillslope erosion, whereas the September storm produced the greatest total channel changes. At both scales, high intensity rainfall above a threshold was responsible for inducing most of the geomorphic change.

1. Introduction

Natural experiments can advance our understanding of landscape evolution and help predict how the earth surface will respond to natural hazards (Tucker and Hancock, 2010; Pelletier et al., 2015). Rain storms after wildfire represent a natural experiment because they often cause substantial geomorphic change. Fires cause loss of ground cover, which leads to decreased infiltration and increased overland flow and surface erosion (Larsen et al., 2009). The increase in surface erosion can cause channel networks to expand through rilling and gullying (Wohl, 2013), which increases hillslope-stream connectivity and sediment delivery to rivers. While these general effects of fire are well documented (Shakesby and Doerr, 2006; Moody et al., 2013), the processes are complex, so predicting post-fire geomorphic change remains difficult. The magnitude of the fire impact varies with: precipitation regime (Moody and Martin, 2009; Wester et al., 2014); site characteristics such as burn severity, topography, and soil erodibility (Moody et al., 2013); time since burning and rate of vegetative regrowth (Benavides-Solorio and MacDonald, 2005); and spatial scale (Moody and Martin, 2009; Wagenbrenner and Robichaud, 2014; Williams et al., 2015). This study focuses primarily on two of these factors, precipitation and spatial scale, and examines the geomorphic effects of different types of rainfall events at hillslope and watershed scales in the Colorado Front Range.

In most of the inner-mountain western U.S., post-fire flooding, erosion, and sedimentation are episodic, primarily triggered by high intensity summer convective storms that produce infiltration excess overland flow (Benavides-Solorio and MacDonald, 2005; Wagenbrenner et al., 2015). High intensity rain storms tend to

Abbreviations: P, storm total rainfall depth in mm; EI_{30}, 30-min rainfall erosivity in MJ mm ha^{-1} h^{-1}; *I*, rainfall intensity in mm h^{-1}; MI_x, maximum rainfall intensity over x-min duration in mm h^{-1}; *P* > *I*, storm total depth (mm) exceeding a 5-min rainfall intensity of *I* mm h^{-1}; *SY*, sediment yield in Mg ha^{-1}; Site names, S = Skin Gulch, H = Hill Gulch, U = upper elevation, M = middle elevation, L = lower elevation.

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dominate total post-fire sediment production (Inbar et al., 1998; Lane et al., 2006; Robichaud et al., 2008). Short-duration (≤30 min) rain intensities have been correlated with peak flow magnitudes and sediment yields (Moody and Martin, 2001; Kunze and Stednick, 2006; Murphy et al., 2015). The convective storms that produce high intensity rains typically are localized (Marco and Valdés, 1998), so unit-area magnitudes of runoff and sediment yield usually decline with increasing drainage area (Marco and Valdés, 1998; Cammeraat, 2004; Mayor et al., 2011; Wagenbrenner and Robichaud, 2014). Short duration, high magnitude pulses of flow can also cause considerable sediment transport and deposition while producing minimal changes in channel shape (Magilligan et al., 2015).

Long duration and/or lower intensity storms can cause runoff and erosion after wildfire (e.g., Morris and Moses, 1987; Ebel et al., 2012), but these types of storms are less likely to generate the infiltration excess overland flow that causes surface erosion. Similarly, snowmelt typically causes very little post-fire erosion at the hillslope scale in this region (Benavides-Solorio and MacDonald, 2005; Wagenbrenner et al., 2015) because short duration snowmelt rates are not usually high enough to generate infiltration excess overland flow. Snowmelt can generate runoff that reaches channels through subsurface pathways (Johnson, 2016), and elevated flows during snowmelt runoff may have the capacity to transport channel sediments (Reneau et al., 2007) and create channel geomorphic change even when hillslope erosion is minimal. Costa and O'Connor (1995) suggested that the geomorphic effectiveness of a flood is related to the time integral of unit stream power above a critical threshold. Events that produce sustained high flows may cause substantial changes in channel geometry, even if they do not produce the highest instantaneous peak flows.

To examine how storm types and spatial scale affect geomorphic response, we compare two spatial scales: hillslope (0.001–0.02 km^2) and channels that drain larger watersheds (0.4–16 km^2) (Fig. 1). During July to September 2013 a sequence of rain storms in the High Park Fire burn area in northern Colorado included: (1) localized, short-duration summer storms, and (2) a widespread long-duration September storm that produced extensive flooding throughout the Colorado Front Range. This combination of rain storms over a relatively short window of time provides a unique opportunity to examine the post-fire geomorphic response to different types of rainfall. We evaluate the geomorphic response to these rain storms at hillslope and watershed scales by comparing: (i) amounts, intensities, and spatial variability of rainfall; (ii) hillslope-scale erosion rates; and (iii) watershed-scale channel stage and cross section changes. These findings can inform predictions of post-fire geomorphic change on hillslopes and in downstream channels and help resource managers assess post-fire risks.

2. Study area

The High Park Fire burned 350 km^2 of primarily forested land in north-central Colorado from 9 June to 1 July 2012. Shortly after the fire, we began monitoring rainfall, hillslope erosion, and channel cross sections in two similar watersheds in the burn area, Skin Gulch and Hill Gulch (Fig. 2). Both watersheds are north-facing and drain directly to the Cache la Poudre River. Skin Gulch is 15.5 km^2, with elevations ranging from 1890 to 2580 m. Hill Gulch is about 5 km to the east, with a 14.3 km^2 drainage area and an elevation range of 1740–2380 m. Pre-fire vegetation in both watersheds was predominantly ponderosa pine (*Pinus ponderosa*) with some mixed conifers, aspen (*Populus tremuloides*), and lodgepole pine (*Pinus contorta*) at the higher elevations of Skin Gulch. Both watersheds burned primarily at moderate-high severity (65% of area), with the high severity burn concentrated in the higher elevation southern portion of Skin Gulch and the northern portion of Hill Gulch closer to the watershed outlet (Fig. 2). Only 13% of Skin Gulch and 18% of Hill Gulch remained unburned. Soils within both watersheds are mostly Redfeather sandy loams derived from Precambrian metasedimentary and metaigneous schists, gneisses, and plutonic igneous rocks (Abbott, 1970). Soils have 10–80% rock content by volume (BAER, 2012).

The climate of the watersheds is semiarid, with mean annual precipitation between 450 and 550 mm (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu). The area experiences a mixed precipitation regime that includes high-intensity thunderstorms during the summer monsoon season from July to early September, frontal storms in the spring and fall, and primarily snowfall during the winter. Both watersheds reportedly had intermittent flow at their outlets before the fire, and hydrologic monitoring of nearby catchments indicates that snowmelt is the largest contributor to runoff in unburned conditions (Johnson, 2016). Prior to burning, the active channels were <1 m wide and generally had only a narrow band of riparian vegetation. Since the burn, the main channels in both watersheds have had perennial flow in many locations, and the highest peak flows have come from rain storms rather than snowmelt.

In the first summer after burning (2012), localized thunderstorms caused severe flooding, erosion, and downstream deposition. The highest flows were in Skin Gulch just one week after the fire, producing an estimated peak flow of 17–30 m^3 s^{-1} km^{-2} (Brogan et al., in revision). We

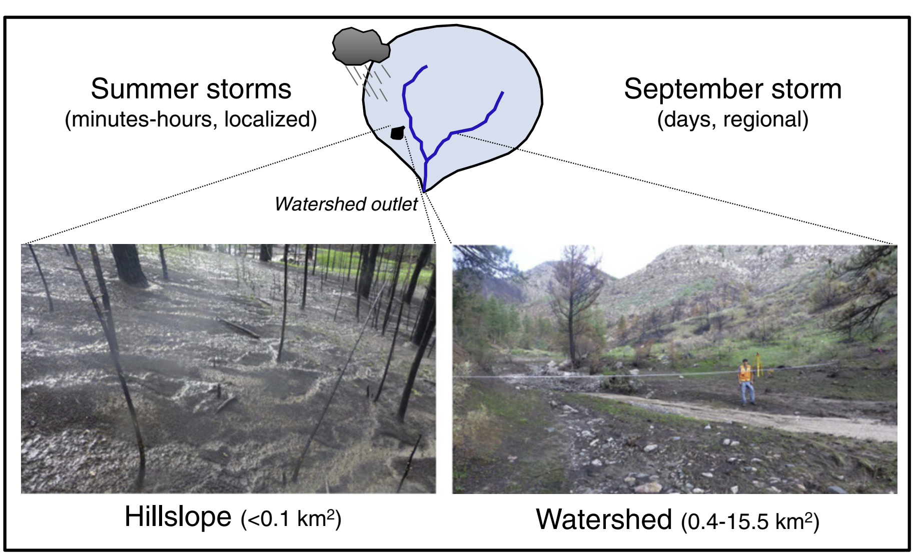

Fig. 1. Conceptual diagram of study design. We compare the geomorphic effects of localized convective summer storms to those of a spatially extensive week-long September 2013 storm at hillslope scale and within channels that drain larger watershed areas.