Scaling Post-fire Effects from Hillslopes to Watersheds: Processes, Problems, and Implications

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Introduction

Over the last two decades we have made considerable progress on understanding and predicting the effects of wildfires on runoff and erosion at the hillslope scale. One cannot, however, sum up the hillslope-scale effects to predict what happens downstream because of the scale-dependent changes in the driving variables and controlling processes; yet resource managers need an understanding and predictive capability to assess post-fire risks at watershed scales, and to prioritize post-fire treatments among watersheds and fires. Our objectives are to: 1) show how post-fire sedimentation effects vary over spatial scales and over time; 2) summarize the results of our four-year study on post-fire erosion and deposition at different spatial scales in two approximately 15 km^2 watersheds after the High Park Fire in northcentral Colorado (Figure 1); and 3) discuss the implications of this and other studies for predicting post-fire sediment deposition and delivery at the watershed scale.

Post-fire Sediment Production and Delivery

Extensive research has shown that the two most important controls on post-fire runoff and erosion in mountainous areas are percent bare soil—which can be inferred from soil burn severity—and rainfall intensity (Benavides-Solorio and MacDonald, 2005). Infiltration rates drop to less than 10 mm hr^{-1} after high and moderate severity fires, so even moderate-intensity rainstorms generate infiltration-excess overland flow. The very low surface cover usually leads to orders of magnitude increases in surface erosion by rainsplash and sheetwash, and the increased runoff causes rilling and a tremendous headward expansion of the channel network (Wohl, 2013). The greater channel density and reduced surface roughness greatly increases hillslope-stream connectivity, resulting in nearly all of the post-fire hillslope runoff and erosion to be delivered to the channel network and transmitted downstream to the lower-gradient channels. In some geomorphic process domains, such as southern California, higher-intensity rainfalls also can lead to devastating debris flows in addition to the more commonly observed increases in hillslope surface erosion (Kean et al., 2011).

In unburned areas sediment delivery ratios almost always indicate that the vast majority of eroded sediment is stored regardless of the size of the area being assessed (Walling, 1983). In contrast, there may be little or no decline in sediment production and delivery rates in the first one to two years after high and moderate severity forest fires for areas up to a few hectares

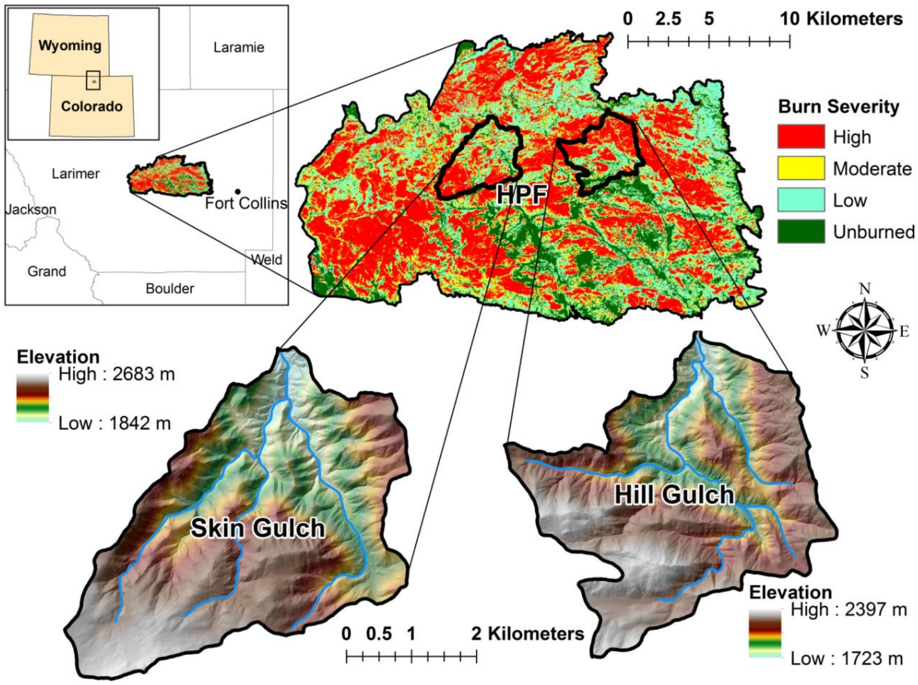

Figure 1. Location and burn severity of the 2012 High Park Fire in northern Colorado just west of Fort Collins, and maps of our two study watersheds where we intensively monitored channel changes using both field methods (cross sections and longitudinal profiles) and post-fire erosion and deposition in the valley bottoms by differencing five sequential lidar datasets.

(Figure 2). Our intensive field surveys and lidar differencing in two 15 km^2 watersheds after the 2012 High Park Fire found that beyond about 1 km^2 the tendency for decreasing channel gradients and confinement caused much of the coarser post-fire sediment to be deposited and stored in the channels and valley bottoms (Figure 3) (Brogan et al., 2019a, b). This predominance of deposition has been documented for a wide variety of post-fire erosion processes (e.g., McPhee, 1989; Benda, 2003). In the Rocky Mountains we've observed that post-fire snowmelt, lower-intensity rainstorms, and higher baseflows do not cause much hillslope erosion, but further downstream the accumulated runoff can erode and transport substantial amounts of the finer and lower-lying post-fire sediment deposits (Figure 3).

After fires the predominant pattern is for the coarse sediments to be readily deposited once stream gradients decline, and this is true for both the debris flows regimes in southern California as well as the much more common fluvially-dominated regimes in most of the western U.S. In contrast, the ash, silts, and clays are readily conveyed to the watershed outlets, resulting in a much higher sediment delivery ratio for these constituents (Figure 4). These finer constituents are often of greatest concern for domestic water providers as they are much more difficult to treat and remove than the coarser particles that can be easily captured in settling basins. A second key observation is that post-fire sediment inputs have a much smaller geomorphic effect in larger streams and rivers because so much sediment is stored in the middle portions of a watershed. The larger streams and rivers downstream of a fire also can readily transport most of the sediment delivered to them, particularly when this is finer-textured. However, post-fire sediment can be a major concern when there are either downstream reservoirs or debris basins with limited sediment storage capacities. For example, post-fire sediment from a succession of fires reduced the storage capacity of Strontia Springs reservoir southwest of Denver by approximately 750,000 m³, and Denver Water spent $30 million in a largely unsuccessful effort to dredge the accumulated sediment.

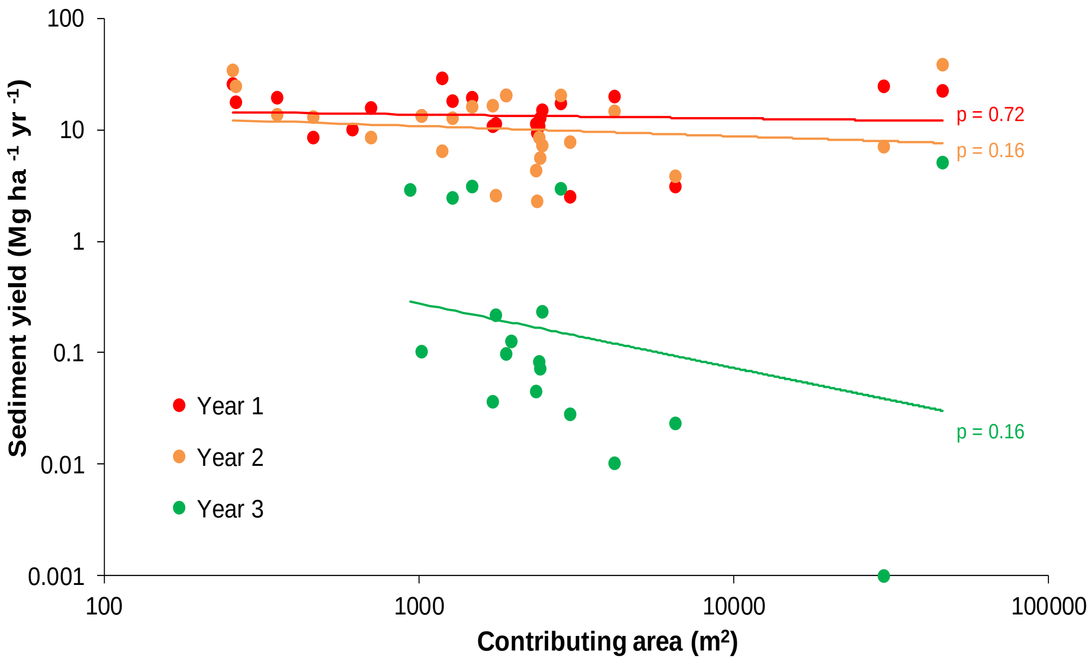

Figure 2. Annual sediment production per unit area for different-sized hillslopes and small watersheds for the second, third and fourth summers after burning following the June 2002 Hayman fire in Colorado. These are labeled as Years 1-3, respectively, as the first summer is immediately after burning, and in this area virtually all of the annual sediment yield is caused by summer thunderstorms. The Year 3 point in the upper right was due to a large storm on one of the two watersheds we were monitoring, while the other small watershed generated no sediment. The former point greatly affects the slope and significance of the Year 3 regression line. For reference one Megagram (Mg) is 1.1 English tons, and 10,000 m² is one hectare or 2.47 acres.

Figure 3. The large amounts of sediment deposited in Skin Gulch after the High Park fire resulted in a very flat valley bottom profile as shown in the picture in the hands of Dr. Peter Nelson. Subsequent snowmelt and lower-intensity rainstorms incised a channel into these deposits and removed some of the finer, lower-lying surface material. Picture was taken in spring 2013, about 11 months after burning.

Post-fire deposition is expected to be particularly high when post-fire runoff and erosion is primarily due to summer convective storms, as the intense rainfall generally falls over a limited portion of a watershed (Kampf et al., 2016) and unit area runoff rates rapidly decline with increasing watershed area. By one to three years after a fire vegetative regrowth sharply decreases overland flow, hillslope erosion, hillslope-stream connectivity, and downslope sediment transport (Benavides-Solorio and MacDonald, 2005; Wohl and Scott, 2017) (Figure 5). These changes cause a corresponding reduction in downstream sediment deposition as well as the high flows needed to erode the initial post-fire sediment deposits.

Figure 4. High flows generated by a summer thunderstorm with high concentrations of suspended sediment and ash at the outlet of the 14 km² Hill Gulch watershed in summer 2012, two months after the High Park Fire.

Figure 5. A rill (light blue dashed line) that had formed almost immediately after burning on a bare convergent hillslope in lower Hill Gulch was largely obscured by regrowth just 14 months later, and did not appear to be actively eroding. The vegetative regrowth would tend to capture sediment and reduce sediment delivery from the hillslope to the stream network.

In the High Park Fire the usual trend of post-fire deposition in downstream areas was completely reversed by a highly unusual, long-duration flood 15 months after burning (Brogan et al., 2019a,b). The sustained high flows had sufficient stream power to scour out nearly all of the post-fire sediment deposits along with much of the pre-existing sediment deposits in the valley bottoms, leaving significantly coarser channels and floodplains (Brogan et al., 2019a,b). We found that the changes in sediment volumes for 50-m long segments of the valley bottom were significantly but usually only weakly correlated with contributing area and valley width, percent area burned at high or moderate burn severity, channel slope, maximum rainfall intensity, and total rainfall (Brogan et al., 2019b).

Current Capabilities and Larger-scale Predictions

Taken together, our results show that accurately predicting post-fire sediment deposition and delivery with increasing watershed area is still beyond our capabilities. On the plus side a process-based understanding—when combined with burn severity, a specified rainstorm, and morphometric data (e.g., channel slope and valley width or confinement)—can help assess relative risks of post-fire flooding, erosion, and deposition in different locations at scales of up to perhaps 20-50 km^2. These assessments can then help decide which sub-watersheds are most likely to either store or transmit post-fire runoff and sediment, and hence which sub-watersheds pose the highest risk for downstream delivery and should have priority for post-fire treatments to reduce hillslope erosion.

As watershed size continues to increase the risks of downstream post-fire flooding and deposition should rapidly diminish for several reasons. First, fires are a mosaic of burn severities and rarely burn all of a large watershed. Hence the large increases in runoff and erosion from areas burned at high and moderate severity are diluted by the much lower runoff and erosion from low severity and unburned areas. Second, high-intensity storms that drive much of the post-fire runoff and erosion are often limited in spatial scale, which leads to rapid declines in unit area peak flows with increasing watershed area. Third, the usual trends for stream gradients to decrease and valley bottom widths to increase with increasing watershed area generally forces relatively rapid deposition of post-fire sediment in the downstream direction. These overall trends do not obviate the tremendous local threats to communities located at the base of a steep mountain front as so tragically observed after fires in southern California. A more explicit identification of the key physical processes and how these change across different spatial scales is essential to better evaluate post-fire risks to life, property, and water quality as well as guide post-fire mitigation treatments.

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