PROCEEDINGS OF THE TWENTY-EIGHTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2015
Union College, Schenectady, NY

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ISSN# 1528-7491

The Consortium Colleges   The National Science Foundation   ExxonMobil Corporation

KECK GEOLOGY CONSORTIUM
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Funding Provided by:
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The National Science Foundation Grant NSF-REU 1358987
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Keck Geology Consortium: Projects 2014-2015
Short Contributions— Fire and Catastrophic Flooding, CO Project

Funding Provided by:
Keck Geology Consortium Member Institutions
The National Science Foundation Grant NSF-REU 1358987
ExxonMobil Corporation

Learning Science Through Research
Published by Keck Geology Consortium

Short Contributions
28th Annual Symposium Volume
25th April, 2015
ISBN: 1528-7491

POST-FIRE HILLSLOPE ASPECT CONTROLS ON EROSIONAL PROCESSES TRACED BY FALLOUT RADIONUCLIDES IN FOURMILE CANYON, COLORADO

EDWARD ABRAHAMS, College of William and Mary
Research Advisor: Jim Kaste

INTRODUCTION

The Front Range of Colorado has a history of high magnitude weather events, including wildfires and floods (Veblen *et al.*, 2000). As recently as 2013, populated areas in the Front Range have made international news due to the massive flooding that occurred there. In September 2010, the region experienced one of the most expensive fires in its history (Graham, 2012), which likely facilitated the flooding. Wildfires have been shown to reduce infiltration by 3-5 times and increase surface runoff, which increases erosion (Ebel *et al*., 2012; Moody and Ebel, 2012; Moody and Martin, 2001; Doerr *et al.*, 2000). Fires are common in the region, and expected to increase in frequency (Graham, 2010, Westerling *et al*, 2006), so it is important to quantify the effects they can have on runoff and erosion rates.

Fourmile Canyon contains Fourmile Creek, a tributary to Middle Boulder Creek (Fig. 1), and displays many features typical of Front Range landscapes. The most notable feature of this area is spatial variance by slope aspect. Fourmile Canyon's south-aspect (northern) face and north-aspect (southern) face differ significantly in slope, plant cover, and moisture content (Graham *et al.*, 2012). This difference has implications for each slope's response to wildfire events, and subsequent erosional response. The recent Fourmile Fire provides an excellent opportunity to observe these differences.

Soil movement can be approximated by tracing radioactive isotopes that adhere to soil particles. Naturally occurring meteoric nuclides Beryllium-7 (^{7}Be) and Lead-210 (^{210}Pb), as well as the man-made fallout nuclide Cesium-137 (^{137}Cs), are commonly used to study close-surface erosional processes. Multiple isotopes with different half-lives are used to track processes that affect different depths in the soil profile: ^{7}Be is short-lived and is only present in the first ~10mm of the soil profile, while ^{210}Pb and ^{137}Cs have longer half-lives and can be found down to 30-50mm (Dethier *et al.*, 2014; Wallbrink and Murray, 1993; Wallbrink and Murray, 1996; Wallbrink, Murray, and Wilson, 1999). Furthermore, by determining an expected nuclide content for the soil in question, zones of denudation and deposition can be identified (Ouimet *et al*, 2014, Kaste *et al*, 2007).

This study uses radionuclide tracers to describe the effects of fire on geomorphic processes in the Fourmile catchment, by analyzing soil core samples along catenas from each slope. To compare the effects of fire on each slope, four transects were sampled: an unburned and burned catena on both the north- and south-facing slopes. Statistical tests demonstrate significantly reduced ^{137}Cs and ^{210}Pb inventories on the burned north-facing slope compared to the other slopes, with the greatest difference present between the two north-facing slopes. This, in combination with the lack of an increased erosion response on the burned south-facing slope, compared to the unburned south-facing slope, suggests that wildfires' effects on erosion rates are aspect-controlled.

STUDY AREA

Lovering and Goddard (1950) describe the geology of the Front Range Mountains in depth. Bedrock for much of the Colorado Front Range consists of a "crystalline core" of Precambrian granites, schists, and gneisses, with some Tertiary sedimentary rocks, and coarse-grained surficial deposits derived from Precambrian bedrock. Dikes and other intrusions of Laramide origin are common in the central areas of the range. Outcrops of these rocks are common along the slopes of the Front Range (USDA-NRCS, 2008).

The soils on the slopes of the canyon are primarily derived from granitic bedrock. Soil surveys classify those on north-facing slopes as primarily sandy clay loam, with a low permeability and higher water capacity than those on south-facing slopes, which are described as dominantly gravelly sandy loam, with high permeability and low capacity (Moreland and Moreland, 2008, USDA-NRCS, 2014). Field observations suggest that the majority of sediments on the slopes in this study were instead silty sands, with a more prominent organic "duff" layer on north-facing slopes.

Typical of Front Range valleys, Fourmile Canyon exhibits steep slopes, with an average of 20°; however, many slopes exceed 45° (Graham *et al.*, 2012; Purinton, 2013). There is an asymmetry between the slopes of the canyon, such that north-facing slopes are steeper than south-facing slopes (Moreland and Moreland, 2008). This asymmetry is largely due to vegetative differences. In the Front Range, north-aspect slopes get less direct sun than south-aspect slopes, and are comparatively moister. Accordingly, plant cover on north-facing slopes is much denser; north aspects are covered by dense forests of Ponderosa pine and Douglas fir, while south aspects exhibit sparser, open stands of pines, with a more significant understory (Graham *et al.*, 2012; Purinton, 2013; Veblen *et al.*, 2007). The slopes of Fourmile Canyon were also rich in Limber pine (David Dethier, personal communication, March, 2015).

Fires in the region are relatively common: the mean fire return interval, describing the period between successive fires for a given area (Veblen *et al*, 2000), in this case the lower montane zone (Kaufmann *et al.,* 2006), ranges from only 8 to 18 years in the Colorado Front Range, and the region as a whole experiences a fire every 2 years on average. Within the last 30 years, there have been at least 3 major fires in the Boulder Creek catchment: the Black Tiger Fire of 1989, Hayman Fire of 2002, and the Fourmile Fire of 2010, as well as many smaller fires (Graham, 2012).

FIELD METHODS

Samples for this study were collected on transects of the slopes of Fourmile Canyon in early to mid-July. Transects were taken on hillside catenas. Four types of slope were identified: North- and south-facing unburned slopes (NFUB and SFUB), and north- and south-facing burned slopes (NFB and SFB). A representative catena was selected for each slope type, based on proximity to 2010 burn (Fig. 1). These transects were roughly centered around Wood Mine, a site that hosted a USGS gauging station before it was destroyed during the flooding in 2013. Wood Mine is in the middle of the Fourmile catchment, ~1.5 miles above the town of Salina (Fig. 1).

In order to ensure a uniform sampling strategy, the slope length of each catena was measured while climbing the hill, using a 50m tape measure. Once the slope length was determined, a sampling interval was chosen such that each slope had 8-10 sampling sites, for a total of 16-20 samples per slope. The soil on the hillslopes displayed significant spatial variance in appearance and thickness, so two samples were taken at each site along the transect. An "A" sample was taken 5 meters down-canyon from the center site, and a "B" sample was taken 5 meters up-canyon. Soil samples were extracted using a tulip-bulb planter, 15 cm long and 7.2 cm in diameter. Soil depth was also measured for each sample, and was defined as

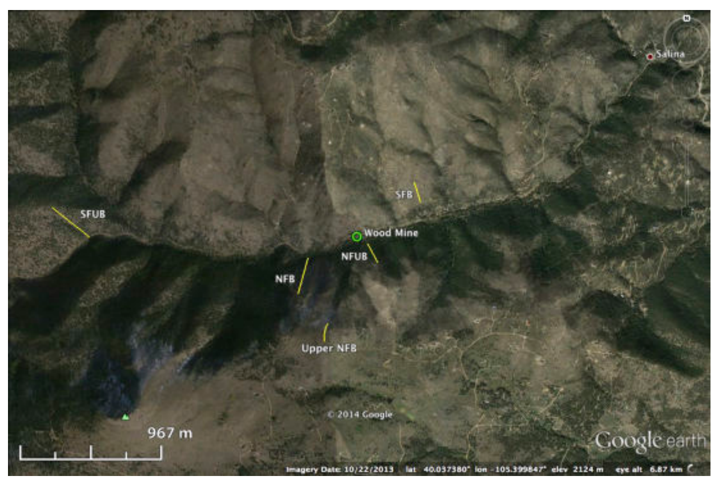

Figure 1. The five major transects taken for this study. Note proximity to Wood Mine and Salina, as well as differences in vegetation between the four slope types. Google Earth, 2014.

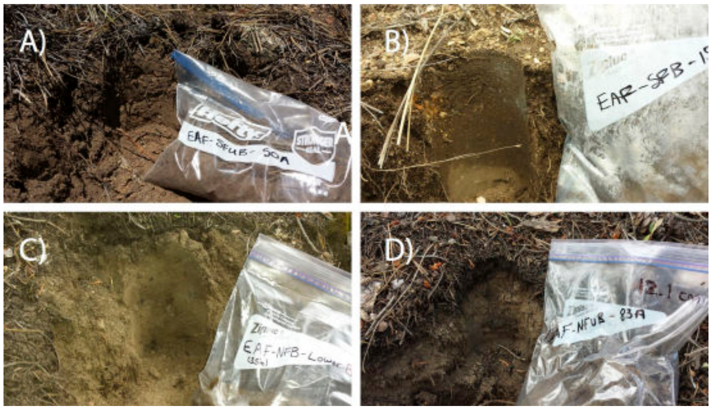

Figure 2. Examples of sediment cores taken in this study. A) is from SFUB, B) is from SFB, C) is from NFB, and D) is from NFUB.

the depth to which the bulb planter could penetrate without solid resistance from boulders or bedrock (Fig. 2).

LAB AND DATA ANALYSIS METHODS

The samples were dried at 105 °C until they reached a constant mass (24-48 hrs), then sieved to separate the >2mm fraction from the bulk sample. The radionuclides used in this study tend to adhere more readily to fine sediments, while coarse sediments retain relatively negligible concentrations (Mondrach, 2013; Blake *et al.,* 2009). Once separated, the <2mm hillslope samples were packed homogenously in 60mL petri dishes, then double-coated with wax to seal them, trapping gases associated with radioactive decay (Keck Consortium, 2014). A 60mL petri dish was used to maximize sample surface area contacting the detector, primarily for ^{7}Be detection.

Samples were analyzed using Canberra Broad-Energy Intrinsic Germanium Detectors, which measure gamma particle emissions associated with decay, using ultra-low background gamma spectroscopy, as in Verplanke (1992). Samples were measured for 100,000-200,000 seconds on average. Radionuclide values were measured as counts of gamma particles at specific energy levels. ^{7}Be peaks were measured at 477 keV, ^{137}Cs at 662 keV, and ^{210}Pb at 46 keV.

^{7}Be values were adjusted for decay, as its half-life is short enough that nontrivial decay occurred between collection and processing of the samples. Atmospheric ^{210}Pb deposition was estimated by calculating "excess ^{210}Pb," or ^{210}Pb that is in excess of what ^{226}Ra can produce in situ as decay daughters. A known point source of ^{210}Pb was used to obtain a transmission rate and to account for absorption of the weak 46 keV gamma (Cutshall *et al.*, 1983). The resulting peak described how effectively gamma particles could penetrate the sample, which was used to normalize the measurements. Final values for all radionuclides were then multiplied by the total <2mm mass of the whole sample, and divided by the area of the coring instrument to obtain Bq/m^2 values of ^{7}Be, ^{137}Cs, and ^{210}Pb for each sample.

After processing, an Analysis of Variance (AnoVa) and subsequent Tukey Honestly Significant Difference (HSD) test was performed on the dataset for each radionuclide. These tests determined, respectively, whether there existed a significant difference between any members of the population, and where such differences were present.

Additionally, samples were categorized by their ^{137}Cs values as sites of accumulation, stability, or erosion

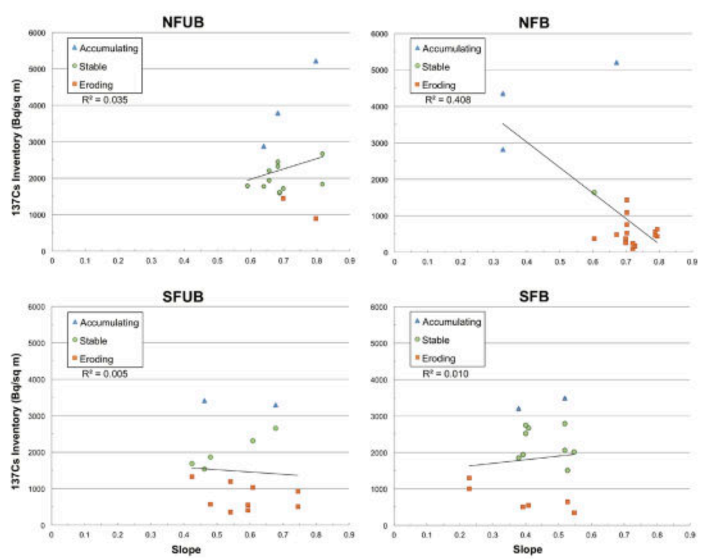

Figure 3. Comparison of ^{137}Cs inventory to slope at each sample location on north-facing slopes. Notably, the NFB slope exhibits an inverse relationship between nuclides and slope, whereas other slopes show no significant correlation. There is an apparent slope threshold for nuclide erosion on NFUB of ~0.7, and a notable shift from stability to erosion between NFUB and NFB. South-facing slopes experience greater levels of erosion than NFUB despite having much lower slopes, and the differences from fire are not notable.

(Fig. 3). ^{137}Cs was chosen as a reference value because it arises from the traceable point source of atmospheric nuclear weapons testing in the 1950s-1960s. To estimate a reference value, the points of least potential disturbance were averaged – these were defined as low-slope values on NFUB (< 0.7), those likely to have the lowest rates of erosion. A range was produced by taking one standard deviation of this set, resulting in a reference range of 1460 – 2800 Bq/m^2.

RESULTS

For all radionuclides in this study, the probability *p* from the AnoVa was below even a 1% confidence threshold, proving that there were statistically significant differences present between some hillslopes in the dataset. A Tukey HSD test was used to supplement the results of the AnoVa, and determine which pairs of hillslopes were significantly different (Table 1). ^{210}Pb and ^{137}Cs showed differences between the pairs NFUB-NFB and NFUB-SFB. ^{7}Be exhibited differences between the pairs NFUB-NFB, NFUB-SFB, and NFUB-SFUB.

Several trends were evident in the nuclide distribution (Fig 4). No slope exhibited a homogenous distribution of radionuclides, nor did the nuclides scale consistently over the whole slope; there was not a simple increase in radionuclide inventory moving downslope, as would be the case with steady, uniform creep. Instead, the distribution tended to be localized on the slope, manifesting as multiple erosion-accumulation cycles. These cycles were characterized by a progressive decrease in radionuclides, moving

Hillslope/Pair	^{7}Be Significance	^{137}Cs Significance	^{210}Pb Significance
NFUB-NFB	$p < 0.05$	$p < 0.01$	$p < 0.01$
NFUB-SFUB	$p < 0.05$	n/s	n/s
NFUB-SFB	$p < 0.01$	n/s	n/s
NFB-SFUB	n/s	n/s	n/s
NFB-SFB	n/s	$p < 0.05$	$p < 0.05$
SFUB-SFB	n/s	n/s	n/s

Table 1. Results of Tukey HSD test. Values show the strength of relationship between hillslope pairs, where n/s is non-significant. The significant pairs for ^{7}Be differ suggest that NFUB has a unique quality in regards to ^{7}Be. Significant pairs for ^{137}Cs and ^{210}Pb, however, indicate that burned slopes are significantly different from NFUB.

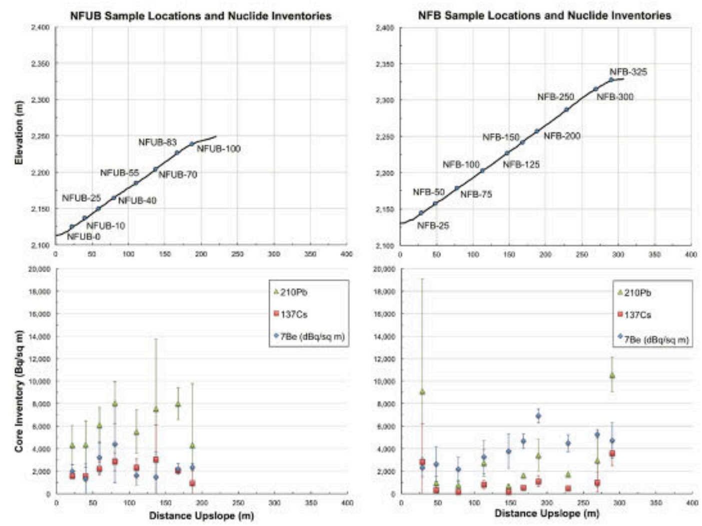

Figure 4a. Hillslope profiles with nuclide inventories in Bq/m2 (7Be displayed in dBq/m2 to make it visible) for north-facing slopes. Nuclide values are represented as the mean of the indicated radionuclide at each site, and error bars are the standard deviation for that nuclide at the site. DEM and LIDAR provided by Will Ouimet.

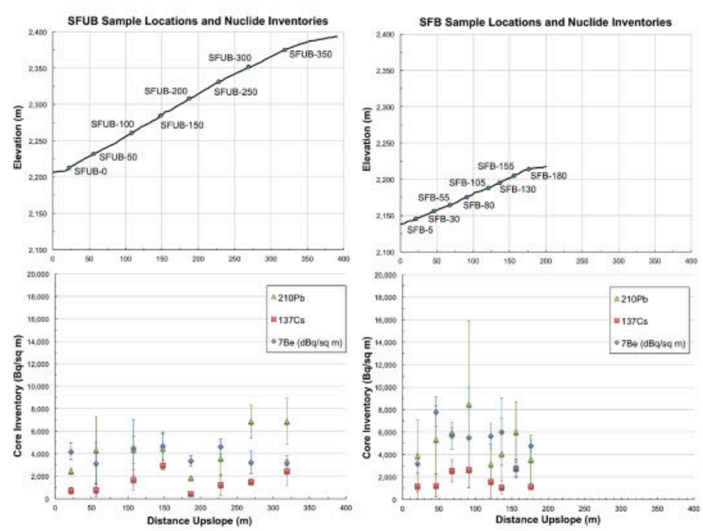

Figure 4b. Same plot as above, for south-facing slopes. Steepness is visibly lower on these profiles, as expected.

downslope, and concluded with a sharp increase in nuclide inventory. For all but NFB, there were roughly two major cycles present. NFB had closer to four of these cycles, and was highly spatially variable, even within sample sites, as evidenced by the high error values.

A comparison of ^{137}Cs inventories to slope value at each sample site gave an approximation of the hillslope's erosional responsiveness to changes in slope (Fig. 3). Only the NFB hillslope demonstrated a relationship between these variables, an inverse correlation, meaning that radionuclide inventories tended to decrease as slope increased. This correlation did not apply to any other hillslope, but the distribution of hillslope state categories (accumulation, stability, erosion) was quite different between the north-facing hillslopes and south-facing hillslopes, as well as between NFUB and NFB.

NFUB was the most stable hillslope, with ~90% of its points either stable or accumulating. Furthermore, its only points of erosion occurred above slopes of 0.7, a relatively steep value for the area. The majority of points on NFB, conversely, were eroding (20% stable/accumulating), at slopes as low as 0.6. The two south-facing hillslopes showed similar trends to one another, but were in contrast to the north-facing hillslopes. Both south-facing hillslopes exhibited erosion at very low slopes, as low as 0.2 on SFB, and had a consistent distribution of accumulating, stable, and eroding points across all slope values. Interestingly, SFB had a higher percentage of non-eroding points (~65%) than SFUB (~45%).

DISCUSSION

The presence of significant relationships, via statistical analyses, between NFUB and the two burned slopes for the deeper isotopes ^{137}Cs and ^{210}Pb, suggests that the influence of fire is significant in regards to "deeper" erosional processes, relative to the isotopes in this study. The fact that the common difference for the pair NFUB-NFB burned status implicating fire as the cause of this result. The pair SFUB-SFB showed no significant difference for any isotope considered, suggesting that the two slopes would share similar radionuclide distributions.

The slope analysis largely supports these conclusions, showing that NFB is primarily eroding, while NFUB demonstrates an opposite trend of stability. Interestingly, and complementing the lack of a statistical relationship, SFB's slope distribution has more in common with SFUB than NFB, even demonstrating a higher level of stability than SFUB. Thus, fire seems to have had little effect on the erosional regime of SFB, but a marked effect on that of NFB. These findings all support the presence of an aspect-controlled fire relevance in this system, suggesting that wildfires will have a major impact on erosion rates in Fourmile Canyon only when they occur on north-facing hillslopes. The data suggest that north-facing hillslopes are generally stable with regard to "deep" erosional processes, but when burns occur, rates of erosion seem to increase drastically. South-facing hillslopes, however, appear to exhibit more consistent and constant erosion at all slope values, likely due to the reduced plant cover, and are not significantly affected by fires with regard to erosion rate.

CONCLUSIONS

The differences in erosional regimes between the north- and south-facing slopes suggest that slope aspect is a control on whether or not wildfires cause a significant increase in erosion rates in landscapes like Fourmile Canyon. Namely, wildfires have a marked effect on north-facing slopes, changing the trend from stability to erosion. Conversely, south-facing slopes are broadly unaffected by fires, instead appearing to tend towards more constant rates of erosion on both burned and unburned slopes.

The interaction observed on the north-facing slopes may suggest that substantial erosion events on these slopes are largely episodic in nature, particularly if fires are followed by heavy rains as occurred in this case. Future studies should investigate whether or not this is the case, and which style of erosion (episodic for north-facing, constant for south-facing) is the more significant contributor of sediment downslope over long intervals.

ACKNOWLEDGEMENTS

I would like to thank my academic advisor for this project, Dr. James Kaste, for his help and guidance in producing my research, and for the use of his lab facilities. I would further like to thank my two project coordinators, Dr. David P. Dethier and Dr. Will Ouimet, both of whom were tremendously helpful in guiding my research both in the field and out of it, and who made my summer research an amazing experience. Additional thanks to Greg Harris, Maneh Kotikian, Rachel Samuels, and Omar Kaufman for their help in the field, climbing up hills and getting all sooty with me on those burned slopes. I would lastly like to thank the Keck Geology Consortium for providing me with this opportunity.

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