HILLSLOPE SEDIMENT ANALYSIS USING FALLOUT RADIONUCLIDES, COLORADO FRONT RANGE

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ABSTRACT

Understanding hillslopes and the transport of hillslope sediment is one of the primary goals of critical zone studies and of the Boulder Creek Critical Zone Observatory (BcCZO) in the Colorado Front Range. This study uses fallout radionuclides, both natural and anthropogenic, as short-term (100-200 yr) sediment tracers to characterize the hillslopes in three main study areas in the Front Range (Gordon Gulch, Betasso Gulch, and the Fourmile Canyon fire area). $^{210}$Pb is a natural fallout nuclide, whereas $^{137}$Cs is a radionuclide that has been falling out of the atmosphere from weapon’s testing in the 1950’s to 1960’s and subsequent nuclear accidents. Soil pits were dug along representative hillslope transects in the study areas and sampled down to saprolite. Gamma spectroscopy was performed on the $<$2 mm fraction of the samples to obtain radionuclide concentrations. Inventories expressing the total amount of each radionuclide in each soil pit were then calculated and used to evaluate their spatial distribution within and across the study areas. Radionuclide concentration at depth was also examined. Short-term data was compared against longer-term (1000-10000 yr) $^{10}$Be data, and variables such as slope angle, slope aspect, wildfire, and vegetation were all examined as possible controls on radionuclide distribution.

The depth profiles of all soil pits display higher radionuclide concentrations in the upper few centimeters that drop off with depth. Soil pits with very steep slope angles have lower radionuclide inventories and may be areas of erosion. A positive correlation between slope angle and radionuclide concentration is indicative of the efficiency of sediment transport, with more efficient transport on steeper slopes. Less vegetative cover on slopes leads to more surface runoff and erosion of surface sediments, meaning lower inventories. Soils with a top ash layer from wildfire have a very high spike in radionuclide concentration in the upper few centimeters from a condensing of both soil and vegetative canopy concentrations. Areas with low surface concentrations may have undergone recent surface stripping. Comparison with longer-term data confirms the observations of this study and allows for an evaluation of short-term events. There is much local variability along each transect, but soil pits exhibit a range of excess $^{210}$Pb and $^{137}$Cs inventories and concentration profiles with depth that are consistent with short-term (<100-200 yr) mobilization, deposition, and erosion of hillslope sediment.
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I. INTRODUCTION

The Critical Zone encompasses the Earth’s topmost layer, from the base of the groundwater to the top of the vegetative canopy. Within this Critical Zone, physical, chemical, and biological processes interact to shape the Earth’s surface. Hillslopes are the direct manifestation of these processes, and understanding the development, structure, history, and movement of hillslope sediment found within naturally evolving landscapes is one of the primary goals of the Boulder Creek Critical Zone Observatory (BcCZO) in the Colorado Front Range (Anderson et al., 2011). Within the BcCZO, multiple focus areas offer the opportunity to study both the short-term and the long-term evolution of hillslopes across a diversity of landscapes. This study focuses on three such areas where short-term radionuclides are used to quantify short-term hillslope evolution.

Short-term radionuclides, with half-lives on the order of tens to hundreds of years, have been used in a number of recent soil-budget studies in order to quantify transport rates of sediments on hillslopes (Wallbrink et al., 2002; O’Farrell et al., 2007). Sediment on hillslopes moves downslope at varying rates depending on specific transport mechanisms, bringing with it radionuclides produced in situ or delivered from atmospheric fallout. In this way, the radionuclides can act as tracers to measure and spatially describe sediment transport (Ritchie and McHenry, 1990). When compared to values from stable sites with little erosion or deposition, excess radionuclide concentrations may indicate deposition, and deficiencies may indicate erosion (O’Farrell et al., 2007).

In this study, the specific fallout radionuclides used are Cesium-137 ($^{137}$Cs) and Lead-210 ($^{210}$Pb), with half-lives of 30.1 and 22.3 years, respectively. These short half-lives make them excellent for tracing short-term (<100 yr) sediment budgets. After initial deposition at the
surface and adherence to sediment particles, subsequent mixing due to transport processes serves to distribute these radionuclides at depth within a soil column (Kaste et al., 2007). $^{137}$Cs is an anthropogenic fallout radionuclide that has been raining out of the atmosphere since extensive weapons testing in the 1950’s and 1960’s. More recently, there has been extensive $^{137}$Cs fallout from the 1986 Chernobyl incident in Russia and the Fukushima Daiichi Nuclear Power Plant accident in Japan following the earthquake and tsunami in March of 2011 (Stohl et al., 2012; Evrard et al., 2012). Known fallout distribution from these events can be used for data regulation and comparison, as fallout was not even, but was dependent on atmospheric factors such as wind and precipitation (Lance, et al., 1986; Baskaran et al., 1993). Despite global variability in fallout, regional concentrations can be assumed to be somewhat uniform. $^{210}$Pb is a naturally occurring radioactive element that is part of the Uranium-238 ($^{238}$U) decay series through the decay of Radium-226 ($^{226}$Ra). As a fallout nuclide, its deposition rate is more constant. In addition to U-series decay and atmospheric fallout, $^{210}$Pb is also produced in situ within sediment and soil, which must be accounted for in sediment inventories (Matisoff and Whiting, 2011). Within sediment and soil, Radium-226 ($^{226}$Ra) can be used to approximate in situ $^{210}$Pb.

Many previous studies using these short-term radionuclides have focused on environmentally disturbed settings such as farmland and land impacted by wildfires or forest clearing (Blake et al., 2009; Wallbrink et al., 2001). More recently, short-term radionuclides have been used to explore transport processes in naturally evolving landscapes (Walsh, 2011). Short-term radionuclide analysis is used here to examine hillslopes in three main study areas in the Boulder Creek Critical Zone Observatory (BcCZO), Front Range, Colorado. The use of $^{137}$Cs and $^{210}$Pb as tracers will allow for a quantitative description of transport and re-distribution
of soils on hillslopes, both spatially and at depth. This study aims to specifically explore the influence of slope and aspect (temperature, water, vegetation) on radionuclide concentration, and characterize the impact of environmental disturbances, such as forest fire. In addition, the short-term data presented here will be compared against long-term (1000-10000 yr) data. Meteoric Beryllium-10 ($^{10}$Be), a cosmogenically derived isotope with a half-life of 1.39 million years, has been used to examine sediment budgets and regolith production in the study area (Shea et al., 2013; Wyshnytzky, 2011). There is a lack of studies involving shorter-lived isotopes in this area, and a comparison of short-term data with long-term data will provide the opportunity for better characterization of sediment transport at various time scales. Overall, the results of this study will contribute to a working model for hillslope transport processes in the lower Front Range in Colorado.

II. STUDY AREA/GEOLOGIC SETTING

The three main areas examined in this study are located within the lower Colorado Front Range west of Boulder. Two study areas lie directly within focus basins of the BcCZO (Gordon Gulch and Betasso Gulch); the third is a ridge top adjacent to Mt. Sugarloaf in the southwestern section of the Fourmile Canyon fire region (Fig. 2). The eastern portion of the BcCZO is argued to be responding to a lowering of stream base level, leading to the incision of deep canyons. Betasso Gulch and Fourmile Canyon are adjacent to these lower canyons, and their dissected topography may reflect a signal from this base level lowering and higher rates of erosion. Gordon Gulch lies within the lower-relief, un-dissected portion of the BcCZO farther west, and is thought to have steady-state surfaces (Anderson et al., 2006).

Gordon Gulch is a catchment that covers an area of roughly 2.7 km$^2$, and is the farthest west and at the highest elevation out of the three study areas. Gordon Gulch flows from west to
east in both the upper and lower parts of the basin, creating definitively north and south-facing slopes. Hillslope gradients in lower Gordon Gulch tend to be steeper than those in upper Gordon Gulch. North-facing slopes in the catchment have a denser vegetative cover primarily consisting of lodgepole pine, and south-facing slopes are more sparsely vegetated with ponderosa pine and surface grasses (Befus et al., 2011). The bedrock geology and parent material of hillslope sediment consists of Precambrian biotite gneiss. There are a number of bedrock outcroppings on both north and south-facing slopes (Anderson et al., 2011).

Betasso Gulch, in Betasso Preserve, is located at a lower elevation to the east of Gordon Gulch, and is much closer to the city of Boulder. The catchment covers an area of approximately 0.46 km², much smaller than Gordon Gulch, and drainage trends primarily from the northwest to the southeast. Lower Betasso Gulch is also characterized by steeper slopes and many bedrock outcrops on the hillslopes, while upper Betasso Gulch is characterized by shallower slopes, soil-mantled hillslopes and thick colluvial deposits within active gullies. The entire catchment has a similar moderate vegetative cover of ponderosa pine stands and intermittent meadows with short grasses. The bedrock underlying the basin is the Boulder Creek granodiorite, which can be seen at a few prominent outcroppings (Befus et al., 2011).

Fourmile Canyon is similar to Gordon Gulch in its west to east drainage and north and south-facing slopes. As with Gordon Gulch, slopes display variation in vegetative cover, with sparse ponderosa pine and grasses dominating south-facing slopes and aspen, douglas fir, limber pine, and abundant grasses and shrubs characterizing north-facing slopes (Ebel, 2013). The bedrock underlying the study area is the Boulder Creek granodiorite with intermittent intrusive dikes, mined throughout the 19th century. In September of 2010, a wildfire swept through the
canyon, burning an area of almost 25 km². Severity of the burn is spatially variable, but both vegetative cover and soils on the hillslopes have been significantly altered (Ebel, 2012).

III. METHODS

Field Methods

In Gordon Gulch and Betasso Gulch, representative hillslope transects (ridgetop to stream) were identified in both the upper and lower parts of the basins. These transects were downslope lines where slope, aspect, and vegetative cover were believed to be locally homogeneous and representative of hillslopes characterizing the portions of each basin. Along each transect, three to four regularly spaced soil pits were dug to a depth below the boundary between saprolite (weathered bedrock) and mobile regolith (Fig. 3). In hopes of capturing $^{137}$Cs and $^{210}$Pb both spatially and at depth, the soil in each pit was sampled at regular depth increments, generally every 4-5 cm, down to 20 to 30 centimeters. Samples were taken from the vertical upslope faces of the pits. Previous studies have demonstrated that short-term isotopes such as $^{137}$Cs and $^{210}$Pb tend to be concentrated in the upper portion of the mobile regolith layer and drop off exponentially with depth (Matisoff and Whiting, 2011). Due to soil sampling methods, each sample represents the given depth and an error range of ~1 cm above and below the sampled depth. At least 150 grams of soil were collected for each sample to ensure that enough would be available for analysis.

Locations for stable reference sites and those in the Fourmile study area were also carefully selected, and the pits were dug and sampled in the same manner. The reference pits are located on ridges above or near the main transects where there is presumed to be little net loss or gain of soil due to hillslope processes (Fig. 4). These are thus fairly low-slope locations, and the isotope profiles from the pits can be compared to the transect pits for soil budget purposes. The
five pits from the Fourmile burn area do not form a transect, but instead represent individual
locations of north and south-facing hillslopes and burned/unburned areas. Two of these pits had
a visible ash layer from the fire.

**Lab and Data Analysis Methods**

Each soil sample was dried at room temperature and then sieved to separate the <2 mm
fraction from the bulk sample. $^{137}$Cs and $^{210}$Pb have been shown to fix preferentially to the fine
fraction of soils, such as clay components, and it is thus assumed that the isotope inventory can
be accurately obtained after eliminating greater particle sizes (van der Perk et al., 2002;
Wallbrink et al., 2002).

Gamma spectroscopy analysis on the <2 mm fraction was performed in collaboration
with James Kaste at the College of William and Mary in Virginia. 40 mL petri dishes with lids
were packed full and counted for generally at least 80,000 seconds, or until error was minimized.
Analytical error for $^{210}$Pb is approximately 4%, error for $^{226}$Ra is approximately 6%, and $^{137}$Cs
has a fixed error of 0.1 Bq/kg. $^{137}$Cs counts were recorded at 662 keV, and $^{210}$Pb counts were
recorded at 46 keV. The photon efficiency for $^{137}$Cs is approximately 4%, and the efficiency for
$^{210}$Pb is approximately 20%. These efficiencies were used to calculate Becquerels per kilogram
(Bq/kg) from the counts per second per kilogram of sample. Radium 226 ($^{226}$Ra) activities were
also recorded as they provide a proxy for in situ production of $^{210}$Pb through $^{226}$Ra decay within
the soil column. Subtracting $^{226}$Ra concentrations from total $^{210}$Pb concentrations gives the
atmospherically derived component of $^{210}$Pb in the sample, identified here as excess $^{210}$Pb
(personal communication with Kaste, December 17, 2012).

Inventories expressing the total amount of $^{137}$Cs and $^{210}$Pb found in each pit are calculated
by first multiplying isotope concentration (Bq/kg) by the thickness of the layer examined (m) and
by the bulk density at that depth in the soil column (kg/m³). All of the products calculated for
the samples in each pit are then summed to obtain a total pit inventory, expressed in Becquerels
per square meter (Bq/m²). Bulk density measurements used in calculating inventories for this
study were calibrated using a dataset of density measurements from over one hundred pits, with
bulk density data at varying depths and soil organic (O), A, B, and C horizons. Error associated
with the bulk densities assumed for this study is 0.1 kg/m³. Total ⁴⁰K and ²¹₀Pb inventories
were calculated here through the use of the midpoint method for evaluating integrals. The
analysis was done on plots of radionuclide concentration at depth. The change in radionuclide
concentration between each data point and the next (Bq/kg) was multiplied by the depth
midpoint between data points (m). This product was then multiplied by the appropriate bulk
density for the sample depth (kg/m³) in order to obtain an inventory value for each sample
(Bq/m²). The values obtained for the samples in each pit were then summed to yield a total
inventory for each pit. Inventory error is found by propagating analytical measurement error,
error in thickness range, and error in layer density.

Inventories for a transect on a south-facing slope in lower Gordon Gulch were obtained in
a different manner due to sampling of only the top 1-2 cm. The radionuclide inventory and
surface concentration of all other soil pits sampled and analyzed were graphed, and a line of best
fit was calculated for each radionuclide (Fig. 5). From these lines of best fit, the known surface
concentrations of the pits in lower Gordon Gulch were used to approximate their inventories.

GIS Methods

A geographic information system (GIS) was used to create elevation maps from available
LiDAR (Light Detection and Ranging) and DEM (Digital Elevation Model) data for each of the
study areas. The LiDAR data (1 m) was utilized for detailed topographic analysis such as making hillslope profiles and slope analysis at each individual pit location.

IV. RESULTS AND DISCUSSION

Depth profiles of $^{210}$Pb and $^{137}$Cs concentration for all pits analyzed to date are compiled in Figure 7 (reference sites), Figure 8 (Lower Betasso Gulch), Figure 11 (Upper Betasso Gulch), Figure 12 (Fourmile Fire region), and Figure 14 (Gordon Gulch). Concentrations in all pits decrease roughly logarithmically, with the highest concentrations near the surface. Concentrations are typically <1% of those near the surface by depths of 8-12 cm, consistent with many previous studies (Kaste et al., 2007; O’Farrell et al., 2007; Walsh, 2011). Among all three study areas, individual pit inventories range from 1172 to 13468 Bq/m$^2$ for excess $^{210}$Pb, and from 266 to 5766 Bq/m$^2$ for $^{137}$Cs (Tab. 1). For Betasso Gulch, the mean excess $^{210}$Pb inventory is 6068 Bq/m$^2$, and the mean $^{137}$Cs inventory is 2003 Bq/m$^2$ (n=5). For Fourmile Canyon, the mean excess $^{210}$Pb inventory is 5548 Bq/m$^2$, and the mean $^{137}$Cs inventory is 2331 Bq/m$^2$ (n=3). For Gordon Gulch, the mean excess $^{210}$Pb inventory is 4713 Bq/m$^2$ and the mean $^{137}$Cs inventory is 1850 Bq/m$^2$. Gordon Gulch thus has the lowest mean inventories of $^{137}$Cs and $^{210}$Pb, but all study areas are comparable in scale. This is consistent with somewhat homogeneous radionuclide deposition across all study areas. However, upon closer examination, the means are not necessarily the best representation of radionuclide patterns within the basins, and much variability exists that seems to suggest non-homogeneous radionuclide deposition.

Betasso Gulch

For Betasso Gulch, inventories for a complete transect in the lower part of the basin are shown in Figure 9, along with a topographic profile along the transect and radionuclide concentrations at depth. Slopes in this lower part of the basin are very steep (>25 degrees),
which is reflected in the topographic profile. $^{210}$Pb inventories for the four transect pits, from top to bottom, are as follows: 6973, 7206, 12269, 4142 Bq/m$^2$. $^{137}$Cs inventories, from top to bottom, are: 1497, 3366, 4812, 1005 Bq/m$^2$. Overall concentrations and inventories of $^{137}$Cs are much lower than those of $^{210}$Pb, but both radionuclides exhibit a similar downslope pattern.

The uppermost pit in the transect, HMB6, has inventories close to the mean inventories for the catchment as a whole. Inventory increases steadily in the next two pits downslope, which may be consistent with a steep slope undergoing downslope transport processes. At the bottom of the transect, the inventories for the lowermost pit (HMB9) drop off significantly, and do not follow the same positive trend. Inventories for both radionuclides in this pit are lower than inventories for the uppermost pit. Long-term radionuclide inventories (meteoric $^{10}$Be), which represent as much as 5000-10000 years and integrate 20-40 cm of total soil depth, do not display the same inventory drop-off at the bottom (Shea et al. 2013). $^{210}$Pb and $^{137}$Cs analyses therefore indicate a loss of radionuclide concentration at the bottom of the transect at a relatively short time scale (<100 yr). This may be due to a short-term erosion event or signal, such as increased incision of Boulder Creek causing the steeper slopes to be more vulnerable to stripping and other transport processes. In all of the pits examined, radionuclide concentration is highest in the upper 8 cm, accounting for the bulk of the total inventory. Lower overall $^{210}$Pb and $^{137}$Cs inventories for the lowermost pit may suggest a recent surface stripping of the upper 4-6 cm of soil, which would remove the depths with the highest radionuclide concentrations and effectively lower the total inventory. The inventories for this pit are also very close to the inventories for HMB14, a reference pit at the top of a transect in upper Betasso Gulch (4142 Bq/m$^2$ excess $^{210}$Pb and 1005 Bq/m$^2$ $^{137}$Cs for HMB9, 4111 Bq/m$^2$ excess $^{210}$Pb and 1448 Bq/m$^2$ $^{137}$Cs for HMB14).
An additional transect was also sampled in upper Betasso Gulch. The top and bottom pits of this transect, HMB14 and HMB15, are very similar in inventory and seem to be consistent with radionuclide transport and deposition at the bottom of the slope. The middle pit in the transect (HMB15), however, has much lower inventories. This may be due to a stripping of surface material from human and animal traffic, or localized natural erosion of the uppermost sediment. However, longer-term $^{10}$Be data for this transect shows the exact same inventory trend (Fig. 10), indicating that there may not be short-term disturbance. Instead, lower isotope levels indicate that this part of the slope is experiencing, and has experienced, erosion as compared to the reference pit (HMB14). The overall range of inventory values for this transect is less than those found in the lower Betasso Gulch transect. This seems to be inconsistent with homogeneous initial basin-wide radionuclide deposition, and therefore suggests that other variables may control initial deposition at the surface. These variables may include vegetation cover or rainfall. Each part of a basin may thus need to be examined separately to draw conclusions about downslope radionuclide transport. In the case of Betasso Gulch, higher inventories in the lower part of the basin may suggest overall transport from the upper to the lower part of the basin, but the large scale of such transport over such a short period of time is unlikely. Another possibility is that slope plays a role in transport rate of soils in Betasso Gulch. The two reference pits in Betasso, HMB6 in lower Betasso and HMB14 in upper Betasso, have inventories of similar scale (Table 1). The slopes of lower Betasso Gulch, however, are approximately twice as steep as those in upper Betasso Gulch (Table 3). Steeper slopes may lead to increased downslope transport and subsequent deposition.
Fourmile Canyon

$^{210}\text{Pb}$ and $^{137}\text{Cs}$ inventories in the Fourmile Canyon Fire region also exhibit spatial variation (Fig. 12). While mean inventory values in Betasso Gulch and Fourmile Canyon are comparable, pits with preserved burn features in Fourmile Canyon demonstrate distinct differences in radionuclide concentration at depth. In the depth profiles of radionuclide concentrations in the Fourmile pits, primarily HMF21 and HMF24, the majority of the radionuclide inventory appears to be concentrated near the surface and drops off dramatically within a few centimeters (Fig. 12). These two pits, when sampled, still had ash remaining at the surface from the Fourmile Canyon Fire. HMF21 was on a moderate slope and covered by a tarp, so much of the surface ash was still in place. HMF24 was uncovered, but near a low slope ridgetop where the ash had not been washed away. HMF22, directly adjacent to HMF21 and at the same slope, had not been covered, and displayed no ash in the upper 5 cm. Radionuclide concentrations and inventories in HMF22 are much lower. The ash may thus be associated with especially high levels of $^{210}\text{Pb}$ and $^{137}\text{Cs}$, perhaps from an accumulation and concentration of the radionuclides from pre-burn upper layers of soil and overlying vegetation. Furthermore, assuming that HMF22 had an ash layer post-fire, the lower amount of $^{210}\text{Pb}$ and $^{137}\text{Cs}$ found in this pit suggests that this ash material was carried downslope and could now be found in gully and valley deposits along Fourmile Creek.

Gordon Gulch

The most notable aspect of the excess $^{210}\text{Pb}$ and $^{137}\text{Cs}$ inventories from the reference pit in Gordon Gulch (HMGG13) is that they are considerably lower than those of the other catchments. The inventories were, in fact, the lowest of all of the pits for which inventory data is available. However, the non-ash hillslope pit from Fourmile (HMF22) has inventories that are
close to these levels (1189 Bq/m² excess $^{210}\text{Pb}$ and 884 Bq/m² $^{137}\text{Cs}$ for HMF22, as compared to 1172 Bq/m² excess $^{210}\text{Pb}$ and 590 Bq/m² $^{137}\text{Cs}$ for HMGG13). If fallout radionuclide deposition rates are locally homogeneous, and the pit in Fourmile Canyon that has such low inventories due to surface stripping, it may be tentatively concluded that Gordon Gulch has also undergone recent surface stripping or erosion in the location of the pit (<100 yr).

HMGG13 was a reference pit for a north-facing transect in lower Gordon Gulch, and the other pits in this transect also show interesting trends (Fig. 13). HMGG10, at the top of the slope, but down from the reference pit, has very high inventories for both radionuclides. The marked increase in inventory from the reference pit to HMGG10 would suggest either rapid and incredible deposition at the top of the slope over a short distance and low slope angle (Table 3), or surface stripping at the reference pit, as previously hypothesized. The middle pit in the transect, HMGG11, also has a much lower inventory than would be expected if sediment were being transported downslope from areas of high radionuclide concentration (HMGG10). This pit, however, was sampled in an area that may have high foot traffic from other studies performed along the same transect, or from wildlife. Also, there may be areas of the slope where natural surface stripping may occur, or localized erosion. A very thick toe slope was present at the bottom of the transect, and the deepest pit in this study was dug and sampled. Along with visible physical deposition of sediment, radionuclide inventories above any other pit sampled in this study support radionuclide deposition. There is thus undoubtedly short-term downslope transport occurring on this slope in lower Gordon Gulch. However, variability exists on the slope itself, and there may have been recent surface stripping in particular areas due to natural or anthropogenic causes. Even though the overall trend is consistent with downslope transport and
deposition, variability in radionuclide concentrations may reflect local erosion and deposition on a smaller scale.

For the north-facing lower Gordon Gulch transect, slope may also play a role in the transport of sediment and observed variability. In the topographic profile (Fig. 13), there is a steep section directly upslope from HMGG10, the second pit from the top, and a low slope at the location of the pit itself (Table 4). A pooling of sediment at this location before being transported downslope may explain the large increase in radionuclide inventory from the reference pit, HMGG13. At the next pit downslope, HMGG11, radionuclide inventories are drastically lower. The slope at this pit is also very steep, approximately 29 degrees. Such a steep slope may lead to an increased rate of downhill sediment transport and increased erosion. There is a still a moderate to high slope angle at the bottom of the slope, but high radionuclide inventories at the sampled pit, HMGG12, indicate deposition. The presence of a toe slope is consistent with high inventories.

The other transect in lower Gordon Gulch was on a south-facing slope. Inventories for the pits in this transect were estimated from radionuclide surface concentrations by comparing inventory to surface concentration for all other soil pits. The overall inventories for these pits are much lower than those found in the north-facing lower Gordon Gulch pits (Table 2). This may be a result of factors related to slope aspect and vegetation cover. The south-facing slopes are far less vegetated, and surface runoff is more likely to occur. This may lead to more short-term erosion of surface sediments on the south-facing slopes, and thus lower inventories. The downslope trends seen in this transect (Fig. 15) may also be a product of slope. Inventories increase slightly from the upper pit to the mid-upper pit, and then increase significantly at the mid-lower pit. Slope decreases from approximately 20 degrees at the mid-upper pit to 16
degrees at the mid-lower pit. Sediment may be moving at a faster rate through the steeper upper part of the slope, whereas farther down, the decrease in slope may lead to slower rates and increased deposition. Radionuclide inventories decrease at the next pit downslope, the lower pit, which coincides with an increase in slope angle to 22 degrees. This is similar to the trend seen on the north-facing slope of lower Gordon Gulch, where a steeper slope may lead to erosion. However, the over-all trend is toward downslope deposition.

The inventories for the two transects in lower Gordon Gulch thus differ in scale, but slope processes and trends seem to be similar. Steeper sections of the north-facing transect are consistent with the greater degree of erosion seen, as represented by more drastic decreases in inventory. From a comparison of the two slopes, it may be concluded that slope aspect itself may not act as a control on sediment transport. However, differences in vegetative cover, which are controlled by slope aspect, do seem to influence radionuclide inventories and sediment transport.

**Transport Efficiency and Mixing Depth**

Figure 6 displays slope vs. inventory for both radionuclides for all soil pits along the sampled transects. In this figure, there appears to be a positive correlation between slope angle and radionuclide inventory, as shown by the trendlines. Very steep slopes, as previously discussed in lower Gordon Gulch, may lead to increased erosion. However, the trend seen in Figure 6 between slope and inventory may describe the over all efficiency of downslope sediment transport. Table 5 shows another indicator of transport efficiency. The maximum slope along each transect is displayed, along with the difference between the highest inventory along that transect and the inventory of the transect’s reference pit. Transects with the highest maximum slope angles, lower Betasso and north-facing lower Gordon Gulch, have greater
inventory ranges. These steeper slopes may thus be capable of transporting material downslope more efficiently, or at a faster rate.

Transport efficiency and slope may also relate to the depth to which radionuclides are mixed within a soil column. Soil pits in locations where there is erosion assumed from slope and total radionuclide inventory seem to have depth profiles that drop off more quickly. By 4-8 cm, these pits display very low radionuclide concentrations. Radionuclide concentrations drop off significantly by a depth of 4 cm in HMGG11, the middle pit in the north-facing lower Gordon Gulch transect with a very high slope angle (Fig 14). Depth profiles are not available for the south-facing lower Gordon Gulch transect, but findings may be similar for the lower pit. Pits where there is deposition assumed from slope angle and radionuclide inventory seem to display greater concentrations at depth. All of the pits along the lower Betasso Gulch transect, for instance, still have notable concentrations at 4-8 cm, along with HMGG10 and HMGG12 in lower Gordon Gulch. Another control on mixing depth is surface disturbance. The depth profiles of soil pits in the Fourmile Canyon fire area with surface ash fall off very quickly. The radionuclides are concentrated in the upper few centimeters of ash, and concentrations below the ash are minimal. This is an example of an environment in which the natural soil mixing processes have been altered.

V. CONCLUSIONS

Soil pits in the BeCZO exhibit a range of excess $^{210}\text{Pb}$ and $^{137}\text{Cs}$ inventories and concentration profiles with depth that are consistent with short-term (<100-200 yr) mobilization, deposition, and erosion of hillslope sediment. Betasso Gulch and the Fourmile Canyon Fire area have comparable inventories, but depth profiles in Fourmile pits display a spike in radionuclide concentration in the upper ash layer, and lower values in one pit suggest stripping of the
radionuclide-rich upper layers. In the lower Betasso Gulch transect, radionuclide inventories increase with distance downslope, but the lowermost pit in this transect displays a sharp decline in inventory for both radionuclides, suggesting a recent erosional or stripping event. Lower inventories also suggest possible short-term erosion and modification. In the upper Betasso Gulch transect, upper and lower pit inventories are consistent with downslope sediment transport, and the middle of the slope may be an area of long-term net erosion. In Gordon Gulch, lower overall inventories on south-facing slopes are consistent with variables related to slope aspect, such as greater amounts of runoff from less and different kinds of vegetation. The north-facing lower Gordon Gulch transect displays an interesting pattern of increasing inventory, followed by a decrease mid-slope, and another marked increase at the toe of the slope. This pattern suggests that erosion and deposition on the slope may be locally variable, but that the overall trend is toward deposition at the bottom of the slope. Slope may be an important control on how soils are moving on the hillslopes, with steeper slopes being areas of faster sediment transport and erosion. This pattern is seen on both slopes in lower Gordon Gulch. Areas of deposition on lower slope angles seem to have greater mixing at depth in the soil column compared to steeper and disturbed slopes. Since the radionuclides used in this study reflect short-term sediment budgets, lower overall inventories in a basin may reflect disturbance or a faster rate at which sediments are being flushed through the basin. The alternative to this is that radionuclide deposition itself is initially variable and sensitive to local differences in wet or dry deposition. An examination of hillslopes on a more local and smaller scale may thus be necessary in order to draw accurate conclusions, rather than cross-basin studies. Regardless, the results of this study demonstrate that sediment on hillslopes in the Colorado front range is being mobilized, eroded, and deposited in measurable amounts on a short-term scale.
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Table 1. Soil pit names and inventories

<table>
<thead>
<tr>
<th>Pit</th>
<th>Excess 210-Pb Inventory (Bq/m²)</th>
<th>137-Cs Inventory (Bq/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMB6</td>
<td>6973</td>
<td>1497</td>
</tr>
<tr>
<td>HMB7</td>
<td>7206</td>
<td>3366</td>
</tr>
<tr>
<td>HMB8</td>
<td>12269</td>
<td>4812</td>
</tr>
<tr>
<td>HMB9</td>
<td>4142</td>
<td>1005</td>
</tr>
<tr>
<td>HMB14</td>
<td>4111</td>
<td>1448</td>
</tr>
<tr>
<td>HMB15</td>
<td>3125</td>
<td>266</td>
</tr>
<tr>
<td>HMB16</td>
<td>4651</td>
<td>1626</td>
</tr>
<tr>
<td>HMGG10</td>
<td>8466</td>
<td>4056</td>
</tr>
<tr>
<td>HMGG11</td>
<td>3500</td>
<td>1233</td>
</tr>
<tr>
<td>HMGG12</td>
<td>13468</td>
<td>5766</td>
</tr>
<tr>
<td>HMGG13</td>
<td>1172</td>
<td>590</td>
</tr>
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<td>HMF21</td>
<td>6835</td>
<td>3046</td>
</tr>
<tr>
<td>HMF22</td>
<td>1189</td>
<td>884</td>
</tr>
<tr>
<td>HMF24</td>
<td>8620</td>
<td>3064</td>
</tr>
</tbody>
</table>

Table 1. Soil pit names, locations, and excess 210Pb and 137Cs inventories for each soil pit. HMB – Betasso Gulch; HMGG – Gordon Gulch; HMF – Fourmile Canyon.
Table 2. South-facing lower Gordon Gulch inventories

<table>
<thead>
<tr>
<th>Slope Position</th>
<th>Excess 210-Pb Inventory (Bq/m²)</th>
<th>137-Cs Inventory (Bq/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>1263</td>
<td>137</td>
</tr>
<tr>
<td>Mid-upper</td>
<td>1814</td>
<td>381</td>
</tr>
<tr>
<td>Mid-lower</td>
<td>4488</td>
<td>1882</td>
</tr>
<tr>
<td>Bottom</td>
<td>3530</td>
<td>756</td>
</tr>
</tbody>
</table>

Table 2. Soil pit locations and excess $^{210}\text{Pb}$ and $^{137}\text{Cs}$ inventories for four soil pits along a transect on a south-facing slope in lower Gordon Gulch. Inventories were estimated from radionuclide surface concentrations by comparing inventory vs. surface concentration for all other soil pits.
Table 3. Angle of slope between soil pits

<table>
<thead>
<tr>
<th>Adjacent Pits</th>
<th>Slope Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMB6 to HMB7</td>
<td>25.88</td>
</tr>
<tr>
<td>HMB7 to HMB8</td>
<td>29.02</td>
</tr>
<tr>
<td>HMB8 to HMB9</td>
<td>28.08</td>
</tr>
<tr>
<td>HMB14 to HMB15</td>
<td>13.17</td>
</tr>
<tr>
<td>HMB15 to HMB16</td>
<td>14.84</td>
</tr>
<tr>
<td>HMGG13 to HMGG10</td>
<td>7.51</td>
</tr>
<tr>
<td>HMGG10 to HMGG11</td>
<td>23.52</td>
</tr>
<tr>
<td>HMGG11 to HMGG12</td>
<td>26.66</td>
</tr>
</tbody>
</table>

Table 3. Angle of slope between adjacent soil pits along three transects. Orange – lower Betasso Gulch transect; Green – upper Betasso Gulch transect; Red – north-facing lower Gordon Gulch transect. Note very steep slopes in lower Betasso Gulch, moderate slopes in upper Betasso Gulch, and low to steep slopes in lower Gordon Gulch.
<table>
<thead>
<tr>
<th>Pit</th>
<th>Slope Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMB6</td>
<td>15.23</td>
</tr>
<tr>
<td>HMB7</td>
<td>29.64</td>
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<tr>
<td>HMB8</td>
<td>32.42</td>
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<tr>
<td>HMB9</td>
<td>20.54</td>
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<td>HMB14</td>
<td>15.44</td>
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<td>HMB15</td>
<td>12.95</td>
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<tr>
<td>HMB16</td>
<td>15.60</td>
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<tr>
<td>HMGG13</td>
<td>1.74</td>
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<tr>
<td>HMGG10</td>
<td>9.68</td>
</tr>
<tr>
<td>HMGG11</td>
<td>28.87</td>
</tr>
<tr>
<td>HMGG12</td>
<td>19.08</td>
</tr>
<tr>
<td>South-facing lower GG Upper</td>
<td>7.36</td>
</tr>
<tr>
<td>South-facing lower GG Mid-upper</td>
<td>19.65</td>
</tr>
<tr>
<td>South-facing lower GG Mid-lower</td>
<td>15.73</td>
</tr>
<tr>
<td>South-facing lower GG Lower</td>
<td>22.47</td>
</tr>
</tbody>
</table>

Table 5. Steepest slopes and inventory ranges

<table>
<thead>
<tr>
<th>Transect</th>
<th>Steepest Slope (degrees)</th>
<th>210-Pb Inventory Range (Bq/m²)</th>
<th>137-Cs Inventory Range (Bq/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Betasso</td>
<td>32</td>
<td>5297</td>
<td>3315</td>
</tr>
<tr>
<td>Upper Betasso</td>
<td>16</td>
<td>540</td>
<td>177</td>
</tr>
<tr>
<td>North-facing Lower</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gordon Gulch</td>
<td>29</td>
<td>12296</td>
<td>5176</td>
</tr>
<tr>
<td>South-facing Lower</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gordon Gulch</td>
<td>22</td>
<td>3224</td>
<td>1745</td>
</tr>
</tbody>
</table>

Table 5. Steepest slope along each transect and difference between highest inventory for each radionuclide and top reference pit inventory. Note greater ranges of radionuclide values for transects with greater maximum slope angles.
Figure 1. Estimated wet deposition density of $^{137}$Cs (Bq/m$^2$) across the United States from global fallout in the 1900’s. Fallout is from global weapons and nuclear testing. (Simon et al., 2004)
Figure 2. Study areas, elevation, and soil pit locations

Figure 2. Elevation maps from LiDAR data of all three study areas together (top) and individually (bottom). Basin extents for Gordon Gulch and Betasso Gulch are outlined in black. Extent of the Fourmile Canyon Fire is outlined in gray. Blue dots in the individual basins represent soil pits dug and sampled but not yet analyzed. Green dots represent soil pits analyzed in this study. All study areas lie within the Boulder Creek Critical Zone Observatory (BcCZO) in the Colorado Front Range to the west of Boulder. Maps were made from available LiDAR (Light Detection and Ranging) and DEM (Digital Elevation Model) data for each of the study areas.
Figure 3. Examples of soil pits dug along representative hillslope transects. Pits were dug to a depth below the boundary between saprolite (weathered bedrock) and mobile regolith, and sampled at regular depth increments, generally every 4-5 cm, down to 20 to 30 centimeters. Previous studies have demonstrated that short-term isotopes such as $^{137}$Cs and $^{210}$Pb tend to be concentrated in the upper portion of the mobile regolith layer and drop off exponentially with depth (Matisoff and Whiting, 2011).
Figure 4. Slope maps of study areas derived from 1 m LiDAR data. Soil pit locations are indicated by black dots, and study areas are outlined in black. Note steeper slopes in the lower parts of Gordon Gulch and Betasso Gulch as compared to the upper parts of the basins, and the overall very steep slopes of lower Betasso Gulch.
Figure 5. Radionuclide inventory vs. surface concentration for all pits sampled and analyzed. Black lines are lines of best fit for each radionuclide.
Figure 6. Slope vs. inventory for all pits

Figure 6. Slope vs. inventory for both radionuclides for each soil pit. Trendlines for each radionuclide follow a positive trend, indicating a positive correlation between slope and inventory.
Figure 7. Reference pit depth profiles

**Figure 7.** Depth profiles of excess $^{210}$Pb and $^{137}$Cs concentrations for reference pits sampled in each basin. Reference pits are located on ridges above or near the main transects where there is presumed to be little net loss or gain of soil due to hillslope processes.
Figure 8. Lower Betasso Gulch transect depth profiles.

Figure 8. Depth profiles of excess $^{210}$Pb and $^{137}$Cs concentrations in soil pits along the lower Betasso Gulch transect.
Figure 9. Lower Betasso Gulch topographic profile and radionuclide inventories

![Figure 9](image)

**Figure 9.** Excess $^{210}$Pb and $^{137}$Cs inventories and meteoric $^{10}$Be inventory for each pit along the lower Betasso Gulch transect (bottom). The soil pit closest to the ridge is HMB6, and the farthest from the ridge is HMB9. Note that at the bottom of the transect, the excess $^{210}$Pb and $^{137}$Cs inventories for the lowermost pit (HMB9) drop off significantly. Meteoric $^{10}$Be does not display the same inventory drop-off, indicating a possible short-term erosion event or signal. Topographic profile (top) displays the steep slopes of lower Betasso Gulch and the locations of soil pits designated by red dots.
Figure 10. Upper Betasso Gulch topographic profile and radionuclide inventories

Figure 10. Excess $^{210}$Pb and $^{137}$Cs inventories and meteoric $^{10}$Be inventory for each pit along the upper Betasso Gulch transect (bottom). The soil pit closest to the ridge is HMB14, and the farthest from the ridge is HMB16. Topographic profile (top) displays the moderate slopes of upper Betasso Gulch and the locations of soil pits designated by red dots. Inventory trends are consistent between short-term $^{210}$Pb and $^{137}$Cs and meteoric $^{10}$Be.
**Figure 11.** Upper Betasso Gulch transect depth profiles

*Figure 11. Depth profiles of excess $^{210}$Pb and $^{137}$Cs concentrations in soil pits along the upper Betasso Gulch transect.*
Figure 12. Fourmile Canyon depth profiles

Figure 12. Depth profiles of excess $^{210}$Pb and $^{137}$Cs concentrations in soil pits sampled in the Fourmile Canyon burn area. Pits with surface ash, HMF21 and HMF24, have concentrations that spike in the upper few cm and drop off quickly with depth.
Figure 13. Lower Gordon Gulch transect topographic profile and radionuclide inventories

Figure 13. Excess $^{210}\text{Pb}$ and $^{137}\text{Cs}$ inventories for each pit along the north-facing lower Gordon Gulch transect (left). The soil pit closest to the ridge is HMGG13, followed by HMGG10 and HMGG11, and the farthest from the ridge is HMGG12. Topographic profile (right) displays the steep slopes of lower Gordon Gulch and the locations of soil pits designated by red dots.
Figure 14. North-facing lower Gordon Gulch transect depth profiles

Figure 14. Depth profiles of excess $^{210}$Pb and $^{137}$Cs concentrations in soil pits along the north-facing lower Gordon Gulch transect.
Figure 15. South-facing lower Gordon Gulch transect topographic profile and radionuclide inventories

Figure 15. Excess $^{210}\text{Pb}$ and $^{137}\text{Cs}$ inventories for each pit along the south-facing lower Gordon Gulch transect (left). Topographic profile (right) displays the moderate to steep slopes of lower Gordon Gulch and the locations of soil pits designated by red dots.