Erosional processes after wildfires: The impact of vegetative ash and the morphology of debris flows

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EROSIONAL PROCESSES AFTER WILDFIRES:
THE IMPACT OF VEGETATIVE ASH AND
THE MORPHOLOGY OF DEBRIS FLOWS

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Presented in partial fulfillment of the
requirements for the degree of
Master of Science
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Erosion and sediment transport increase following wildfires. Overland flow and debris flows are the dominant processes that increase post-wildfire erosion. The impact of vegetative ash on post-wildfire overland flow and debris flows has been implied by some studies. The swelling of vegetative ash may clog soil pores and increase runoff. In addition, vegetative ash has been hypothesized to be a critical component in the generation of post-fire debris flows. This project is separated into two studies: (1) the physical and chemical characterization of vegetative ash and (2) the morphology of post-wildfire debris flows.

The physical and chemical properties of naturally-occurring and experimental ash samples were analyzed using laser diffraction, elemental analysis, ICP-MS, and XRD. The naturally-occurring ash was collected from the 2005 Tarkio, Montana wildfire. The mean Tarkio fire ash particle density and median particle size are $2.5 \pm 0.6 \ g/cm^3$. The median particle size ranged from 127 to 136 $\mu m$. The mean percent carbon and nitrogen of the Tarkio fire ash are 11.4 % and 0.4 %, respectively. The major chemical constituents of the Tarkio fire ash are calcium, potassium, magnesium, phosphorous, manganese, iron, and aluminum. The mineral composition of the Tarkio ash is comprised primarily of calcite, quartz, sulfates, and feldspars. Experimental ash samples were produced by combusting different fuel types at different combustion temperatures. The vegetative ash samples produced by combusting Ponderosa Pine limbs and needles at 450 and 600 °C best simulate the elemental content and mineral composition of the Tarkio fire ash.

Post-wildfire debris flows were generated in the Sleeping Child creek basin by intense convective storms in 2001. These debris flows initiated by progressive sediment bulking. Initiation of debris flows by progressive bulking is indicated by rill networks and slope-area thresholds. Landslide initiation of debris flows is not evident. The mean debris flow-scoured gully expansion rate is $0.006 \pm 0.002 \ m^2/m$. The SCC debris flow-scoured gullies are characterized by steep gully heads, generally continuous gullies, mud coating and nick marks on adjacent trees, log and boulder jams, and levees in the lower portion of the gullies. The impact of wildfires and debris flows in forming landscapes is supported by the SCC debris flows.
Preface

The topics of this thesis have been written in two chapters. Each chapter has been written as a stand alone scientific paper. The papers have been written in the appropriate format for submission in the journal of Geomorphology, Elsevier Press. The first chapter is a discussion of experimental results for the physical and chemical characterization of vegetative ash. The first chapter will be submitted to Soil Science for publication. The second chapter covers a field study regarding the morphology of post-wildfire debris flow. The second chapter will be submitted to Geomorphology for publication.
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Physical and Chemical Characterization of Vegetative Ash

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Abstract

The presence of fine sediment (e.g. silt and clays) has been related to an increase in post-wildfire erosion and debris flows. The influence of vegetative ash on increased erosion and debris flows has been inferred by some studies. However, few studies have specifically examined the physical and chemical properties of vegetative ash. This study characterizes the vegetative ash from a natural wildfire and twenty laboratory-produced vegetative ash samples. The physical and chemical properties of these vegetative ash samples were analyzed using laser diffraction, elemental analysis, ICP-AES, and XRD.

Three 2005 Tarkio, Montana ash samples were collected and analyzed. The mean Tarkio fire ash particle density and median particle size are 2.5 ± 0.6 g/cm³. The median particle size ranged from 127 to 136 μm. The mean percent carbon and nitrogen of the Tarkio fire ash are 11.4 % and 0.4 %, respectively. The major chemical constituents of the Tarkio fire ash are calcium, potassium, magnesium, phosphorous, manganese, iron, and aluminum. The bulk mineral composition of the Tarkio fire ash is comprised of calcite, quartz, and anorthite. The clay fraction (< 2 μm) mineral composition of the Tarkio fire ash is comprised of calcite, sulfates and some feldspar minerals. The vegetative ash samples produced by combusting Ponderosa Pine limbs and needles best simulate the elemental content and mineral composition of the Tarkio fire ash.
Keywords: vegetative ash, debris flows, wildfire, XRD, ICP-AES, laser diffraction

1. Introduction

It is commonly observed that runoff and erosion increase dramatically after wildfires (Swanson, 1979; Meyer and Pierce, 2003; Shakesby and Doerr, 2006). Overland flow and debris flows are particular effective in increasing post-wildfire sediment transport (Parrett, 1987; Wells, 1987; Meyer and Wells, 1997; Cannon and Reneau, 2000; Cannon et al., 2001). Soil hydrophobicity is typically identified as the cause of increased post-wildfire runoff (DeBano, 1981; Neary et al., 1999); however, soil hydrophobicity is generally spatially discontinuous and patchy, which may limit the extent and duration of its impact on post-wildfire runoff (Morin and Benyamini, 1977; Huffman et al., 2001; Martin and Moody, 2001). Alternatively, soil pore clogging due to swelling of vegetative ash may cause surface sealing and increase runoff and sediment transport after wildfires (Etiegni and Campbell, 1991).

Vegetative ash may be important in the generation of progressively bulked debris flows. Field studies (e.g. Meyer and Wells, 1997; Cannon et al., 2001) have shown that fines content (e.g. clay, silt, and vegetative ash) is a significant fraction of post-wildfire debris flow deposits. Laboratory studies (Cao and Qian, 1990; Julien and Lan, 1991; Major and Pierson, 1992) indicate that the presence of fines (<2 mm size fraction) can increase the viscosity of sediment slurries, hence decreasing the fall velocity of entrained sediments. Julien and Lan (1991) found that suspensions of clay and silt containing between 15 and 45 percent by volume solids can have dynamic viscosities of 1.5 to 4 orders of magnitude greater than the viscosity of clear water. It is thought that debris flow yield strength is promoted by the cohesion of clays and by intergranular friction.
between abundant fine particles (Pierson and Costa, 1987). The role of vegetative ash, however, in post-wildfire debris flow initiation has only been inferred by the above studies.

Vegetative ash, therefore, may play a critical, but underappreciated, role in post-wildfire erosion. This is not surprising considering the large quantities of vegetative ash generated during wildfires. For example, Goforth et al. (2005) report average ash thickness of 6-8 mm for the mixed pine and oak forests burned in southern California and Cannon et al. (2001) report ash thickness up to 5 cm for the Cerro Grande fire, New Mexico. In addition, vegetative ash was several centimeters thick after the 2005 Tarkio, Montana wildfire (S. Woods, unpublished data).

There have been some studies of ash relevant to runoff and erosion. Ulery et al. (1993) found that wood ash can increase soil pH by up to 3 pH units (to pH 10.5). This change in soil pH is a result of the alkalinity of vegetative ash, which ranges from 8 to 13 (Etiegni and Campbell, 1991; Naylor and Schmidt, 1986; Goforth et al., 2005). The pH of ash is attributed to carbonates and bicarbonates at combustion temperatures below 500 °C and to oxides for temperatures above 1000 °C (Naylor and Schmidt, 1986). Misra et al. (1993) also found that ash carbonates dissociate to oxides at higher combustion temperatures. Vegetative ash has the potential to swell and clog soil pores, decreasing soil infiltration, and increasing overland flow (Ralston and Hatchell, 1971). Etiegni and Campbell (1991) found that ash may expand up to 12.5% in volume when wetted. The swelling of ash when wetted is attributed to the expansion of calcium silicate hydrate and portlandite minerals (Etiegni and Campbell, 1991). The mineral composition of wood ash is comprised of carbonates, sulfates, silicates, and oxides and varies with combustion
temperature (Etiegni and Campbell, 1991; Misra et al., 1993; Ulery et al., 1993; Goforth et al., 2005). The chemical constituents in vegetation may accumulate by precipitation from the atmosphere (Dongarra et al., 2002) or by the dissolution of minerals into groundwater and subsequent uptake by plant roots (Vyshemirskii and Simonova, 1988; Misra et al., 1993). The minerals found in vegetative ash may have been transported to the plant by root uptake or may be formed during combustion (Misra et al., 1993).

The purpose of this study is to characterize the physical and chemical properties of vegetative ash created by wildfire. It is important to understand vegetative ash as a geologic material. This analysis will provide fundamental knowledge regarding the properties (e.g. density, particle size distribution) that may affect runoff and erosional processes. We analyze the physical and chemical properties of naturally-occurring ash and experimental ash produced from different fuel types combusted at different temperatures. The comparison of experimental and natural ashes is important, because ash may need to be produced for use in future experiments (e.g., infiltration and runoff simulations). In addition, we hope that the analysis of vegetative ash produced from different fuels combusted at different temperatures may elucidate physical and chemical differences of vegetative ash produced by different intensity wildfires.

2. **Materials and Methods**

2.1 **Natural Ash Collection**

Three ash samples were collected from the burn area of the 2005 wildfire near Tarkio, Montana, which is located approximately 70 kilometers west of Missoula, Montana. This wildfire was better known as the Interstate 90 (i.e. I-90) fire, but will be referred to in this paper as the Tarkio fire. The Tarkio fire began on August 4, 2005 and
was contained on August 17, 2005. The Tarkio fire burned in open areas of grass, shrubs, and conifers. All grass, surface litter, and tree limbs and needles were combusted. The conifers in this region are a mixture of Ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), Lodgepole pine (*Pinus contorta*), sub-alpine fir (*Abies lasiocarpa*), and western larch (*Larix occidentalis*). The primary lithology in the burn area is low-grade metasedimentary rocks of the Belt Supergroup (Lonn and Smith, 2005). The Tarkio fire burned in a high-relief area with elevations ranging from approximately 950 to 1900 m. Three ash samples were collected from the Tarkio fire area on August 25, 2005 and are arbitrarily denoted as Tarkio #1, #2, and #3 ash samples. The ash collected was a whitish, gray color. The Tarkio ash samples are used in this study to represent natural wildfire ash.

2.2 Experimental Ash Production

2.2.1 Burn Barrel Ash Production

Four ash samples were created using a burn barrel. The burn barrel used was fashioned from an approximately 110 L galvanized steel garbage can equipped with a burning grate, ventilation ports, and a removal base for ash collection. The ash samples were produced by combusting four different fuels: (1) Ponderosa Pine (P. Pine) needles and (2) limbs, (3) a collection of native grasses, and (4) a representative sample of an A-horizon forest soil (i.e. duff layer). The fuels combusted were collected near Missoula, Montana. The P. Pine needle and limb fuels were collected from slash piles from a forest thinning operation. The grass and duff fuels were collected *in situ*. All fuels were oven-dried for approximately 24 hours at 40 °C prior to combustion. The mineral soil was not separated from the duff layer sample. The fuels were ignited using a propane torch. The
ambient air temperature and combustion temperatures of the four fuels were monitored using thermocouples connected to a Campbell CR10 data logger. Combustion temperatures were collected at the base of the fuel, within the burning fuel, approximately 2.5 centimeters above the top of the fuel, and approximately 5 centimeters above the top of the fuel. The mean high temperatures were 572, 1160, 707, and 491 °C for the burn barrel combustion of P. Pine needles, P. Pine limbs, grasses, and duff layer, respectively. The approximate combustion durations were 1.7, 2.8, 1.5, and 5.8 hours for the burn barrel combustion of P. Pine needles, P. Pine limbs, grasses, and duff layer, respectively. The ash content was 4.7, 2.3, 24, and 78 percent of the unburned fuel for the burn barrel combustion of P. Pine needles, P. Pine limbs, grasses, and duff layer, respectively. The duff layer only smoldered, producing a mixture of ash and mineral soil. The smoldering of the duff layer is indicated by the longer combustion duration and the presence of mineral soil is indicated by the high ash content of the ash combusted from the duff layer.

2.2.2 Muffle Furnace Ash Production

Sixteen ash samples were produced in a Barnstead-Thermolyne 62700 muffle furnace. The different fuel types were combusted at four temperatures to produce sixteen ash samples. The four fuels combusted were P. Pine needles, P. Pine limbs, grasses, and duff layer. In contrast to the burn barrel experiment, the mineral soil was separated from the duff layer by submerging the duff in water and agitating it. The mineral soil separation was performed to allow more thorough combustion than with the burn barrel experiment, and to produce an ash sample that did not contain mineral soil chemical constituents. All fuels were oven-dried for approximately 24 hours at 40 °C prior to
combustion, except for the duff layer which was dried for 27 hours at 75 °C. The duff layer was oven-dried at a higher temperature and for a longer duration to ensure complete drying following the mineral soil separation. The four fuels were combusted in the muffle furnace at 450, 600, 800, and 950 °C for three hours. The mean ash content for the four combustion temperatures was 3.1 ± 0.4, 4.1 ± 3.0, 10 ± 3.0, and 60 ± 7.1 percent of the unburned fuel for the muffle furnace combustion of P. Pine needles, P. Pine limbs, grasses, and duff layer, respectively.

2.3 Particle Density Measurement

The particle density was measured for the three Tarkio fire ashes. The particle density was determined through measurement of the bulk density and porosity of the ash samples (Tisdall, 1951).

2.4 Particle Size Distribution

Particle size distribution measurements were performed for the three Tarkio fire ash samples by laser diffraction using a Malvern Mastersizer 2000. Each ash sample was analyzed with a 12-second, 52 detector scan. Thirty 12-second scans, with a one second lag between each scan, were performed for each sample run and five sample runs were performed on each Tarkio ash sample. No sample sonication was performed on the ash samples and a pump rate of 2000 rpm was used. For each sample run, 0.31 mL of ash was suspended in approximately 500 mL of a 5.5 g/L sodium hexametaphosphate solution. Sodium hexametaphosphate solution was used to ensure entrainment of ash particles and to disaggregate any ash aggregates. The sample obscuration was held between 10 and 15% for optimum instrument performance (Sperazza et al., 2004). The Malvern Mastersizer 2000 software version 5 was used to analyze the grain-size
distributions. For the Mastersizer grain-size analysis, a reflectance value of 1.5 and an absorbance value 1.0 were used.

2.5 Elemental Analysis

The percent carbon and nitrogen of the Tarkio, burn barrel, and muffle furnace ashes were measured using a CE Instruments Elemental Analyzer. Manual separation of char (i.e. partially combusted fuel) from the ash samples was performed prior to elemental analysis. Manual separation was achieved by using tweezers to remove char particles. This process, however, did not entirely remove the char; hence the elemental analysis measurements may overestimate the percent carbon of the ash samples. Ash samples were then homogenized and pulverized before being analyzed.

2.6 Inductively Coupled Plasma – Atomic Emission Spectrometry

The concentrations of the primary chemical constituents were measured in five ash samples with a TJA IRIS Inductively Coupled Plasma Atomic Emissions Spectrometer (ICP-AES). Sample preparation and digestion were performed following U.S. EPA method 3050B (U.S. EPA, 1996). The ICP-AES operation and quality control were performed following U.S. EPA method 6010 (U.S. EPA, 1996). The following ash samples were selected for ICP-AES analysis: Tarkio fire #1, P. Pine limbs combusted at 450, P. Pine limbs combusted at 950 °C, P. Pine needles combusted at 950 °C, and grasses combusted at 450 °C. These ashes were chosen to allow comparison of natural wildfire ash with experimental ash produced from different fuels combusted at the two temperature extremes. The ICP-AES analysis was performed by the Geology Environmental Biogeochemistry Laboratory at the University of Montana – Missoula.
The percent difference in the chemical constituent concentrations of the four experimental ashes compared to the Tarkio fire ash was calculated as:

\[
\text{Percent Difference} = \left\{ \frac{[T] - [\text{Exp}]}{[T]} \right\} \times 100 \tag{1-1}
\]

where \([T]\) and \([\text{Exp}]\) are the constituent concentrations (mg/kg) of the Tarkio ash and an experimental ash, respectively. The experimental ash samples were considered to closely compare to the Tarkio fire ash if the percent difference was less than 25%.

2.7 X-ray Diffraction

The mineral compositions of the bulk and clay (<2 μm) fractions of the ash samples were analyzed using a Philips X-Ray Diffractometer using a CuK radiation source and a graphite crystal monochronometer. The bulk ash samples were prepared according to the following steps. Four percent silicon standard, as determined by weight, was added to the ash and the ash and silicon mixture was pulverized using mortar and pestle. The resultant fine powder was mixed with approximately 0.5 mL deionized water, added to a glass slide, and the sample was allowed to dry under a heat lamp. The clay fraction of the ash samples was prepared according to the following steps: approximately 0.2 grams of ash was mixed with 40 mL of deionized water, the mixture was sonicated for approximately one minute to completely disperse and mix the ash, and the sample was centrifuged at 1000 rpm for two minutes. Then the supernatant was decanted and evaporated under a heat lamp. The resultant clay fraction powder was prepared by the same method described above for the bulk ash samples. These sample preparation techniques result in oriented ash samples for XRD analysis.

The XRD analysis of the bulk and clay fraction ash samples was performed from 2.5 to 75 degrees 2θ (i.e., 44.14 to 1.26 Å). The Philips XRD was operated at 40
kilovolts and 30 milliamps for all the XRD analyses. The resultant XRD spectra were smoothed by a weighted mean method using the MacDiff 4.2.5 software (Petschick, 2001). The mineral compositions of the ash samples were determined using the ICP-AES chemical compositions and the following mineral databases: (1) MacDiff 4.2.5 (Petschick, 2001), (2) the 1974 and 1986 Joint Committee of Powder Diffraction Standards, and (3) the Walker and Renault (1972).

3. Results

3.1 Particle Density

The particle densities for the Tarkio ash samples are 2.6, 2.3, and 2.6 g/cm$^3$ for samples #1, 2, and 3, respectively. The mean particle density of all three Tarkio ash samples is 2.5 ± 0.6 g/cm$^3$.

3.2 Particle Size Distribution

The particle size distribution is initially bimodal and progresses to a unimodal distribution with time (Figure 1.1). The particle size change is due to particle and aggregate degradation by the Mastersizer impeller-induced turbulence and grain-to-grain collision. Since the ash particles degrade when processed through the Mastersizer impeller, the original size of the ash particles could not be determined directly from the laser diffraction results. The first laser diffraction measurement of particle size is performed 13 seconds into the analysis (Figure 1.2). There is an initial increase in median particle size (i.e., $D_{50}$) for the first three laser diffraction scans, followed by an approximately exponential decline (Figure 1.2). The maximum mean $D_{50}$ particle size for the Tarkio ash is 136 ± 18 μm. The mean $D_{50}$ particle size at 13 and 390 seconds are 127 ± 22 μm and 59 ± 10 μm, respectively.
3.3 Elemental Analysis

The percent nitrogen and carbon values generally decrease with increased combustion temperature (Figures 1.3a and 1.3b). The nitrogen content was highest for combustion temperatures <500 °C and declined at temperatures >600 °C (Figure 1.3a). The percent carbon is dependent on the fuel type and generally decreases with increasing temperature (Figure 1.3b). However, the decrease in carbon content with increasing combustion is less consistent than for the nitrogen content trend. This inconsistent trend of decreasing carbon content with increasing combustion temperature may be due to inconsistency in the method used to separate char from the ash samples (see section 2.5). The lack of complete char removal may have caused the increase in carbon content between the P. Pine limb ashes combusted at 600 and 800 °C (Figure 1.3b).

3.4 Ash chemical composition

The major chemical constituents (greater than 0.5% by weight) of the five ash samples analyzed by ICP-AES are calcium, potassium, magnesium, phosphorous, manganese, iron, and aluminum (Figure 1.4a). None of the chemical constituents of the experimental ashes exactly match the Tarkio ash, an expected result given that the Tarkio ash was created from an unknown mixture of fuels at an unknown temperature. Nonetheless, the experimental ash created from P. Pine limb ash combusted at 950 °C provides the best match to the Tarkio ash (Table 1.1).

3.5 Ash mineral composition

The Tarkio ashes are comprised of calcite, quartz, and anorthite (Table 1.2a). The P. Pine limb and needle experimental ashes are also comprised of calcite and several different species of silicate and feldspar, whereas the duff and grass ashes are comprised
of only quartz and anorthite (Table 1.2a). The clay fraction of the Tarkio fire ash samples are comprised of calcite, sulfates and some feldspar minerals (Table 1.2b). The clay fractions of the experimental ashes are primarily comprised of a combination of carbonates, silicates, feldspars, sulfates, oxides, and evaporites (Table 1.2b).

The clay fraction XRD analysis indicates a wider variance in the vegetative ash mineral composition for the less than 2 μm size fraction, than in the bulk samples. For instance, calcite is present in the clay fraction of a few of the duff ash samples, but was not present in the bulk samples. This discrepancy may be due to masking of low concentration minerals by more prevalent minerals in the bulk sample analysis. That is, for the clay fraction analysis the higher concentration, larger minerals may be separated out and no longer mask the low concentration, smaller minerals. Example bulk and clay fraction XRD spectra are shown for the Tarkio ash sample #2 (Figures 1.5a and 1.5b).

The XRD samples were analyzed in an oriented alignment using the glass slide method and hence do not provide a quantitative measure of mineral concentrations (Moore and Reynolds, 1997, pp. 215). In addition, the XRD spectra obtained for the ash samples contained substantial background noise. This noise is likely due to the size segregation caused by the glass slide sample preparation method (Moore and Reynolds, 1997, pp. 214) and due to mineral compounds that diffract at similar angles and result in overlapping mineral peaks. The background noise of the XRD spectra made identification of specific mineral compounds within a mineral group (e.g. feldspars) difficult for some ash samples.
4. **Discussion**

Post-wildfire increases in overland flow may be impacted by the presence of vegetative ash. Surface sealing by ash has been suggested as one mode of increased overland runoff and erosion following wildfires (Morin and Benyamini, 1977; Neary et al., 1999). Etiegni and Campbell (1991) suggest that, during wetting, lime and silica may react to form calcium silicate hydroxide. The expansion of calcium silicate hydrate and portlandite minerals in vegetative ash may cause particle swelling and soil pore clogging (Etiegni and Campbell, 1991). The original particle size of vegetative ash is a measure of the size of particles that may be washed into soil pores after a wildfire. The original median particle size ranged between 127 and 136 μm for the Tarkio ash. Etiegni and Campbell (1991) report an average particle size of 230 μm for ash produced from Lodgepole pine sawdust. Soil pore size is typically discussed in terms of micropores (<0.5 μm), mesopores (0.5 — 50 μm), and macropores (>50 μm) (Ashman and Puri, 2002). Soil macropores vary in type and size (Beven and Germann, 1982), but are typically of sufficient size to accommodate the particle size of vegetative ash. In addition, we found that the naturally-occurring and experimental ashes were comprised of carbonates, silicates, oxides, sulfates, and feldspars, depending on the combustion temperature. Hence, the vegetative ash analyzed in this study has the properties necessary to potentially enter soil macropores, expand when wetted, clog soil pores, and cause decreased infiltration and increased runoff.

The physical properties of vegetative ash reported here are useful to understanding the impact of vegetative ash on the initiation and rheology of post-wildfire debris flows. The mean Tarkio fire ash density of $2.5 \pm 0.6 \text{ g/cm}^3$ is only slightly less dense than the
density of quartz, 2.65 g/cm$^3$, calcite, 2.71 g/cm$^3$, and anorthite, 2.76 g/cm$^3$ (Deer et al., 1992). This result implies that the density of the Tarkio fire ash is primarily due to residual minerals present in the ash. The presence of organic material results in vegetative ash being slightly less dense than the residual minerals. The particle density of vegetative ash will determine the particle settling velocity of ash in debris flows and the grain-to-grain interaction of ash with other debris flow entrained particles. The final particle size of the laser diffraction analysis is a measure of the particle size vegetative ash entrained in debris flows. The mean final particle size of the Tarkio fire ash is 59 ± 10 µm. This particle size can be used to estimate the impact of vegetative ash particles on debris flow rheology.

The particle size decreased exponentially with laser diffraction analysis duration (Figures 1.1 and 1.2). However, the first three laser diffraction scans (39 sec) display an initial increase in particle size (Figure 1.2). This increase in particle size may be due to the inability of the Mastersizer to entrain large, irregular-shaped, lower density ash aggregates. The pump rate of 2000 rpm is optimum for small particle size analysis (Sperazza et al., 2004), but may not completely entrain larger particles or aggregates. In addition, the particle size distribution of Tarkio ash #1 is initially unimodal and becomes bimodal with time (Figure 1.1). This result suggests that medium and coarse ash particles may be initially bound in particle aggregates. The large size fraction peak in the initial particle size distribution may be due to only a few particle aggregates. The continued processing of the ash sample through the laser diffraction impeller breaks up these particle aggregates, because of grain-to-grain collisions and impeller-induced turbulence. The comminution of the ash aggregates results in the unimodal particle size distribution.
and median particle size decrease. We suggest that this process is similar to the natural process of particle comminution from the transport of ash particles entrained in overland flow and debris flows.

The nitrogen and carbon content results show a close comparison between the Tarkio fire ash samples and ash produced by combustion of P. Pine needles at 450 and 600 °C, suggesting that the Tarkio fire ash samples may have been produced by combustion of pine needles at combustion temperatures in the 450 to 600 °C range. The percent nitrogen of both the P. Pine limb and needle ashes combusted at 450 °C is similar to that of the Tarkio fire ash (Figure 1.3a). In addition, there is no detectable nitrogen in the ashes combusted at temperatures greater than 450 °C (Figure 1.3a). Misra et al. (1993) note that the nitrogen content of wood ash is typically insignificant due to conversion of wood nitrogen to NH$_3$, NO$_x$ and N$_2$ gases during combustion. The P. Pine needle ash samples combusted at 450, 600, and 800 °C are the only experimental ashes that have similar carbon content to the Tarkio ash (Figure 1.3b). The percent carbon is dependent on the fuel type and generally decreases with increasing temperature (Figure 1.3b). The above elemental analysis trends may be useful as a post-wildfire estimate of combustion temperature. As discussed above, the percent nitrogen is volatilized at temperatures above 450 °C and the percent carbon is dependent on the fuel type and decreases with increasing combustion temperature. Hence, wildfire combustion temperatures could potentially be estimated by the percent nitrogen and carbon of wildfire ash samples. In addition, the relationship between combustion temperature and both carbon and nitrogen content may be useful for evaluating soil nutrient budgets after wildfires.
The major chemical constituents of the five ash samples analyzed by ICP-AES are calcium, potassium, magnesium, phosphorous, manganese, iron, and aluminum (Figure 1.4a and Table 1.1). This result is similar to that found in other studies. Misra et al. (1993) found the major wood ash elements for a variety of wood types to be calcium, potassium, magnesium, sulfur, phosphorous, and manganese. Etiegni and Campbell (1991) found the major chemical constituents of Lodgepole pine wood ash to be calcium, potassium, magnesium, silicon, and phosphorous. In addition, the ICP-AES results indicate that the experimental ashes are composed of the same major chemical constituents as the Tarkio ash (Table 1.1); however, the experimental ashes generally have a greater percentage of the major chemical constituents than the Tarkio fire ash (Table 1.1). This may be due to the loss of chemical constituents by chemical degradation or dispersion processes (e.g., wind, sublimation, microbial uptake, etc) in natural wildfire settings.

Misra et al. (1993) found that the mineral composition of ash samples was controlled by the type of wood combusted and the combustion temperature. The fuel type controls the chemical constituents and minerals available during combustion and the combustion temperature controls the chemical reactions that occur. Some mineral compounds will decompose at higher temperatures, whereas other minerals are not stable below a temperature threshold. For instance, Misra et al. (1993) show that ash mass loss in the 650-950 °C temperature range is due to decomposition of calcite (CaCO₃). After 900 °C, ash mass loss is due to the decomposition of potassium carbonate (K₂CO₃) or calcium and magnesium sulfates (Misra et al., 1993).
The calcite decomposition temperature at atmospheric pressure is 894 °C (Deer et al., 1992, pp. 627). In this study, calcite is present in the bulk and clay fraction of the P. Pine limb ash combusted at 950 °C and in the clay fraction of the P. Pine needle ash combusted at 950 °C (Tables 1.2a and 1.2b). In addition, calcite was not present in the bulk duff ash samples, but was present in the duff ash combusted at 450, 600, and 800 °C (Table 1.2b). The presence of calcite in the clay fraction of the duff samples, but not in the bulk samples, may be due to mineral size and concentration (see section 3.5). The presence of calcite at 950 °C, and only in the clay fraction of the duff samples, suggests that clay size calcite particles are able to persist above the calcite decomposition temperature, because they may be bound in an ash aggregate during combustion, thus insulating them from the highest temperatures.

The mineral compositions of the ashes produced by combusting P. Pine limbs and needles are most similar to the Tarkio ash (Tables 1.2a and 1.2b). This is true for ash produced in either the burn barrel or in the muffle furnace. Of the P. Pine limb and needle ashes combusted using a muffle furnace, the mineral composition of the ashes combusted at 450 and 600 °C is most similar to the Tarkio ash (Tables 1.2a and 1.2b). The XRD results suggest that different fuel types and combustion temperatures will result in an ash sample with different mineral composition. Hence, the characteristics of natural wildfire ash samples will also vary with available fuel type and fire severity. The laboratory production of wildfire ash should account for this natural variability.
5. **Conclusions**

This study evaluated the physical and chemical properties of natural wildfire vegetative ash collected from the 2005 Tarkio, Montana wildfire. Three vegetative ash samples were collected from the Tarkio fire. The Tarkio ashes were analyzed for particle density, particle size using laser diffraction, nitrogen and carbon content using elemental analysis, chemical composition using ICP-AES, and mineral composition using XRD. The mean particle density for the Tarkio ash is $2.5 \pm 0.6 \text{ g/cm}^3$. The mean original particle size ranged from 127 to 136 $\mu$m. The final particle size is $59 \pm 10 \mu$m. The mean percent carbon and nitrogen of the Tarkio ash are 11.4 and 0.4, respectively. The major chemical constituents (greater than 0.5% by weight) of the Tarkio ash are calcium, potassium, magnesium, phosphorous, manganese, iron, and aluminum. The bulk mineral composition of the Tarkio ash is comprised of calcite, quartz, and anorthite. The clay size (< 2 $\mu$m) mineral composition of the Tarkio ash is comprised of calcite, feldspars, and sulfates. The mineral composition of the clay size fraction of the Tarkio ash is more variable than the bulk mineral composition. This may be due to masking of low concentration, smaller size minerals by higher concentration, larger minerals in the bulk sample analysis.

The Tarkio ash was compared to experimental ash produced from four fuel types: Ponderosa Pine (P. Pine) limbs and needles, grass, and forest soil duff layer. These fuels were combusted over a range of combustion temperatures (450 to 1160 °C) using both a burn barrel and a muffle furnace. The nitrogen and carbon contents of vegetative ash decrease with increasing combustion temperature. The XRD mineral composition results proved the most useful analysis method in the comparison of the natural wildfire and
experimental ash samples. The mineral composition of the ash samples produced by combusting P. Pine limbs and needles, at combustion temperatures ranging from 450 and 600 °C, were most similar to the mineral composition of the Tarkio ash. The chemical and mineral composition of ash samples vary with fuel type and combustion temperature. Hence, to simulate a natural wildfire ash in the laboratory the natural wildfire ash must first be characterized. The results of this study provide a foundation of physical and chemical properties for vegetative ash.

6. Acknowledgements

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7. References


Figure 1.1. Laser diffraction particle size distributions for vegetative ash sample collected from the 2005 Tarkio, Montana wildfire. The grain-size distribution is initially bimodal. The median grain-size decreases during analysis due to particle and/or aggregate breakdown. The final grain-size distribution is unimodal. Each curve represents a different sample time, which are denoted, in seconds, by the number above each curve peak.
Figure 1.2. Median particle size ($D_{50}$) decreased with time during the laser diffraction analysis, because of particle and aggregate degradation. The mean $D_{50}$ at 13 and 390 seconds is 127 ± 22 and 59 ± 10 μm, respectively.
Figure 1.3a. Nitrogen content (%) of the Tarkio and muffle furnace ash samples decreases with increased combustion temperatures. The mean nitrogen content of Tarkio ash #1 is shown at 550 °C. The combustion temperature of the Tarkio ash is unknown, however comparison to the experimental ashes suggest combustion temperatures between 450 and 650 °C. The combustion temperatures for the experimental ashes were measured using four thermocouples located at the fire base, within the fuel, 2.5 cm above the fuel, and 5.0 cm above the fuel. The experimental combustion temperatures reported in this figure are the mean high temperatures for the four thermocouples.
Figure 1.3b. Carbon content (%) of the Tarkio and muffle furnace ash samples decreases with increased combustion temperatures. The lack of complete char removal may have caused the carbon content between the P. Pine limb ashes combusted at 600 and 800 °C. The mean carbon content of Tarkio ash #1 is shown at 550 °C. The combustion temperature of the Tarkio ash is unknown, however comparison to the experimental ashes suggest combustion temperatures between 450 and 650 °C. The combustion temperatures for the experimental ashes were measured using four thermocouples located at the fire base, within the fuel, 2.5 cm above the fuel, and 5.0 cm above the fuel. The experimental combustion temperatures reported in this figure are the mean high temperatures for the four thermocouples.
Figure 1.4a. Major chemical constituents (> 0.5%) as determined by ICP-AES analysis.
Figure 1.4b. Minor chemical constituents (< 0.5%) as determined by ICP-AES analysis.
Figure 1.5a. X-ray diffraction spectrum for the bulk sample of a natural wildfire ash sample collected in the burn area of the Tarkio, Montana wildfire (Tarkio sample #2). Analysis of the bulk sample identifies all minerals present in an ash sample. The counts were smoothed using a weighted mean method to eliminate peak noise in the spectrum. The following symbols denote peaks representing minerals that are present in this ash sample: Si = silicon standard, 1 = calcite, CaCO₃, 2 = quartz, SiO₂, and 3 = anorthite, CaAl₂Si₂O₈.
Figure 1.5b. X-ray diffraction spectrum for the clay fraction (<2μm) sample of a natural wildfire ash sample collected in the burn area of the Tarkio, Montana wildfire (Tarkio sample #2). The counts were smoothed using a weighted mean method to eliminate peak noise in the spectrum. The following symbols denote peaks representing minerals that are present in this ash sample: Si = silicon standard, 1 = calcite, CaCO₃, 2 = gypsum, SiO₂, and 3 = anorthite, CaAl₂Si₂O₈.
Table 1.1 – ICP-MS chemical constituent concentrations (mg/kg) for the Tarkio, Montana wildfire and select experimental ashes. The experimental ashes were selected to represent a range of fuel types and combustion temperatures. Bold values indicate a cl

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PQL = practical quantification limit (lower reporting limit); % columns are the percent difference between the ash sample value and T1 avg. b.d. = below detection = concentration < PQL; T1a = Tarkio #1 sample A; T1b = Tarkio #1 sample B; T1avg = mean of T1a and T1b; L450 and L950 = P. Pine limbs combusted at 450 and 950 °C, respectively; N950 = P. Pine needles combusted at 950 °C; G450 = grasses combusted at 450 °C.
## Table 1.2a - Bulk X-Ray Diffraction results for vegetative ash samples.

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X = mineral/compound present in ash sample, ? = questionable mineral match and/or similar mineral compound present (e.g. another feldspar silicate), T1 = Tarkio ash #1, T2 = Tarkio ash #2, T3 = Tarkio ash #3, BBG = burn barrel duff layer ash, BBL = burn barrel P. Pine limb ash, BBN = burn barrel P. Pine needle ash

## Table 1.2b - Clay Fraction (< 2um) X-Ray Diffraction results for vegetative ash samples.

| Mineral / Compound | Structure | JCPDS | T1 | T2 | T3 | BBD | BBG | BBL | BBN | 450°C | 600°C | 800°C | 950°C | 450°C | 600°C | 800°C | 950°C | 450°C | 600°C | 800°C | 950°C |
|--------------------|-----------|-------|----|----|----|-----|-----|-----|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| **Carbonates**     |           |       |    |    |    |     |     |     |     |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| Calcite            | CaCO₃     | 05-0586 | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| **Silicates**      |           |       |    |    |    |     |     |     |     |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| Quartz             | SiO₂      | 33-1161 | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Opal               | SiO₂ₓH₂O  | 38-0448 | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| **Feldspars**      |           |       |    |    |    |     |     |     |     |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| Anorthite          | CaAl₂Si₂O₆ | 41-1486 | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Diopside           | CaMg(SiO₃)₂ | 11-0654 | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Gehlenite          | Ca₂Al₂SiO₇ | 35-0755 | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Omphacite (Na₂Ca)(Al,Mg)Si₂O₆ | 42-0568 | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Forsterite         | Mg₂SiO₄   | 34-0169 | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| **Sulfates**       |           |       |    |    |    |     |     |     |     |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| Arcanite           | K₂SO₄    | 05-0613 | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| **Evaporites**     |           |       |    |    |    |     |     |     |     |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| Sylvite            | KCl       | 04-0587 | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |

X = mineral/compound present in ash sample, ? = questionable mineral match and/or similar mineral compound present (e.g. another feldspar silicate), T1 = Tarkio ash #1, T2 = Tarkio ash #2, T3 = Tarkio ash #3, BBG = burn barrel duff layer ash, BBL = burn barrel P. Pine limb ash, BBN = burn barrel P. Pine needle ash
Abstract

Debris flows are more frequent following wildfires. Post-wildfire debris flows are important geomorphic agents that shape landscapes and impact stream channels. Many debris flows were generated after wildfires in the Sleeping Child creek (SCC) basin, southwest Montana. These debris flows were generated by intense convective storms and initiated by overland flow erosion and progressive sediment bulking. Initiation of debris flows by progressive bulking is indicated by rill networks and slope-area thresholds. Landslide initiation of debris flows is not evident. The mean debris flow-scoured gully expansion rate is 0.006 ± 0.002 m²/m. The SCC debris flow-scoured gullies are characterized by steep gully heads, generally continuous gullies, mud coating and nick marks on adjacent trees, log and boulder jams, and levees in the lower portion of the gullies. The rill networks converge at the gully heads and are characterized by discontinuous, shallow (1 to 4 cm) rills. The impact of wildfires and debris flows in forming landscapes is supported by the SCC debris flows.

Keywords: debris flow, wildfire, gully, slope-area threshold, landscape evolution
1. **Introduction**

Wildfires typically increase hillslope erosion rates. Post-wildfire erosion can be increased by denudation, soil hydrophobicity and disaggregation, dry ravel, overland flow, and debris flows. Hillslope denudation following wildfires can decrease soil cohesion by removing the root mat (Cannon and Reneau, 2000) and increase raindrop impact and splash erosion by eliminating vegetation interception (Neary et al., 1999). In addition, denudation can eliminate vegetation buffering of hillslope mass wasting and decrease the surface roughness (Cannon and Reneau, 2000). Soil hydrophobicity and disaggregation can occur due to volatilization and condensation of soil organic matter during wildfires (DeBano, 1981; Neary et al., 1999; Mataix-Solera and Doerr, 2004). Post-wildfire soil hydrophobicity and disaggregation result in loose, friable surface soil (DeBano, 1981; Neary et al., 1999). This easily erodible soil can be transported downslope by dry ravel, thin debris flows, and overland flow (Moody et al., 2005). Dry ravel is the gravity-driven downslope transport of unconsolidated sediment by rolling, bouncing, and sliding (Wells, 1987; Gabet, 2003). Thin debris flows occur when the upper 1-3 cm of soil becomes saturated above a hydrophobic layer and the pore pressures become sufficiently high to trigger a shallow landslide which mobilizes as a thin debris flow (Wells, 1987; Gabet, 2003). Post-wildfire rill networks develop due to storm-generated overland flow and can transport large quantities of sediment downslope (e.g., Wells, 1987; Cannon et al., 2001). Debris flows, however, provide the most dramatic example of accelerated erosion after a wildfire (e.g., Parrett, 1987; Wells, 1987; Meyer and Wells, 1997; Cannon and Reneau, 2000; Cannon et al., 2001).
Debris flows can initiate due to soil slip failures (Iverson et al., 1997) and progressive sediment bulking of loose, friable surface sediment (Wells, 1987). Post-wildfire debris flows typically initiate due to progressive sediment bulking, not soil slip failures. This is evident by the presence of extensive rill networks and the absence of landslide scarps upslope of post-wildfire debris flows (e.g., Parrett, 1987; Wells, 1987; Meyer and Wells, 1997; Cannon and Reneau, 2000; Cannon et al., 2001). The importance of vegetative ash to the initiation of post-wildfire debris flows has been suggested by some studies (e.g., Parrett, 1987; Cannon et al, 2001). Cannon et al. (2001) found vegetative ash to comprise a critical portion of the fine (<2 mm) sediment fraction of hillslope runoff for a debris flow-generating storm. In addition, Cannon et al. (2001) report a lack vegetative ash in hillslope runoff for post-wildfire storms that did not generate debris flows.

Debris flows are important agents of geomorphic change. Debris flows can deliver large pulses of sediment to stream channels (Reneau et al., 1990; Benda et al., 2003; Hoffman and Gabet, 2006). Channel morphology can be significantly impacted by large sediment pulses. Miller and Benda (2000) observed channel widening and braiding, fining of bed material followed by coarsening, construction of coarse grained terraces, and formation of new side channels following debris flow sediment inputs. Hoffman and Gabet (2006) observed channel aggradation due to fine grained sediment upstream of debris flow fans, channel narrowing and coarse-grained terrace formation through debris flow fans, and channel widening and braiding downstream of debris flow fans. In addition, debris flows are important agents of landscape evolution. Stock and Dietrich (2003) postulate that debris flow activity is the primary process shaping steep headwater
valleys. Post-wildfire debris flows may play a significant role in landscape evolution by controlling bedrock channel incision, valley dissection, and mountain range elevation.

Changes in stream morphology due to debris flow sediment pulses can have positive and negative impacts on stream ecology. Benda et al. (2003) found that debris flow sediment pulses increase the physical heterogeneity of low-order stream channels. Channel heterogeneity can maintain diverse and productive aquatic habitats (Resh et al., 1988; Poole, 2002). In addition, debris flows can deliver large woody debris (LWD) to stream channels (e.g., Miller and Benda, 2000; Benda et al., 2003; Hoffman and Gabet, 2006). In-channel LWD has been positively correlated to pool formation (Montgomery et al., 1995; Beechie and Sibley, 1997) and increased bull trout spawning habitat (Carnefix, 2002). In contrast, fine sediment inputs from debris flows may cover salmonoid spawning habitat (Carnefix, 2002). Furthermore, channel aggradation due to large pulses of sediment inputs and subsequent incision can isolate riparian communities from floodplain disturbance and sediment inputs. Flood disturbance and nutrient addition from sediment input are important to riparian plant communities (Naiman et al., 1993; Bendix and Hupp, 2000; Dwire and Kaufman, 2003).

Numerous debris flows were triggered in steep, colluvial hollows in the Sleeping Child Creek (SCC) basin in 2001. The SCC basin is located in the Sapphire Mountains of southwest Montana (Figure 2.1). Over 75% of the upper SCC basin burned in the Valley Complex fires of August 2000 (Hyde, 2003). Intense convective storms in July 2001 triggered at least 16 debris flows in the burned region of the SCC basin (Hyde, 2003; Hoffman and Gabet, 2006). The rainfall intensity for these storms ranged from between 4.1 and 16.8 mm/hr in the lower SCC basin (Hyde, 2003). The rainfall intensity,
however, was likely greater in the burned portion of SCC, where steeper slopes and higher elevations would increase the orographic storm effects. Photographs of two debris flow-scoured gullies in SCC are shown in Figures 2.2 and 2.3.

The purpose of this study is to evaluate the hillslope and gully morphology relationships of post-wildfire debris flows. The gully head location, gully head drainage area, slope at the gully head, volume of sediment scoured, and gully width-to-depth ratios were evaluated for the SCC debris flows. From this analysis, we hope to determine trends between gully and hillslope morphometric parameters that elucidate the processes involved in post-wildfire debris flow initiation.

2. Materials and Methods

2.1 Field Site

Six debris flow-scoured gullies, and eight tributary debris flow-scoured gullies of those gullies, are evaluated in this study. The debris flow-scoured gullies are located in the Sleeping Child Creek (SCC) basin, which is located approximately 15 kilometers south of Hamilton, Montana (Figure 2.1). The drainage area of the SCC basin is 169 km$^2$, the basin elevation ranges between approximately 1200 to 2250 m, and has a mean elevation of 1900 m. The average annual precipitation is 79 cm/yr and is characterized by snowfall from November to March (Hoffman and Gabet, 2006). The underlying lithology of the basin is predominately gneiss and granite (Hyde, 2003). The hillslopes are mantled by sandy loam with abundant gravels that often move readily under foot (Hyde, 2003). Talus slopes and bedrock outcrops are abundant within SCC. The vegetation in SCC prior to the 2000 wildfire was comprised of 53% Douglas fir (Pseudotsuga menziesii), 18% Lodgepole pine (Pinus contorta), and 19% Ponderosa pine
(Pinus ponderosa) (Hyde, 2003). Land use impacts have been light in the study area of the SCC basin. No logging or roads are present, except for a short segment of forest service road in the southeast corner of the basin. Four rarely-used recreational trails are present and are located along the divides and the main channel of SCC. Prior to 2000, the previous wildfire recorded in SCC occurred in 1889 (Hyde, 2003). The burn severity from the 2000 Valley Complex fires was uniform across the study area. Hyde (2003) classified the burn severity in the study area as moderate to high severity using NEXRAD imagery and the normalized burn ratio (NBR) technique.

2.2 Debris Flow Gully Surveys

Field surveys of six SCC debris flow scoured gullies were performed between June and August 2005. The location of debris flow indicators (e.g., levees, sediment deposits, nick marks on trees, etc) were recorded with a handheld GPS. The location of gully heads and mouths, the beginning of rill networks that contributed to gullies, and measured gully cross-sections were also recorded. The horizontal GPS accuracy in the SCC drainage was between six and ten meters depending on the location within the drainage and the time of day.

2.2.1 Longitudinal Profiles

Gully longitudinal profiles were measured from a 1:24 000 scale topographic map (USGS Quadrangle: Bald Top Mountain). The GPS waypoints from the field surveys were used as a rough guide to locate each debris flow scoured gully and major gully characteristics (e.g., incision point and cross-sections) on the topographic map.

2.2.2 Cross-sections
Gully cross-sections were measured with a tape measure and stadia rod. The locations of the cross-sections were chosen to represent uniform reaches of the debris flow gullies. At least five cross-sections were measured for each debris flow gully. The cross-sectional area of each gully cross-section was calculated by plotting each cross-section on a grid of known area and counting the grid cells within the cross-section. The original soil surface in the colluvial hollows where the debris flows initiated was unknown. Hence, three cross-sectional areas were calculated for high, median, and low original soil surfaces. The shape of these three original soil surfaces was drawn to mimic the contour of the gully cross-section. The high, median, and low original soil surfaces were drawn arbitrarily. The original soil surface can also be estimated using hillslope morphology and gradient adjacent to the gully. We chose, however, to use a range of arbitrary original soil surfaces due to the uncertainty of original soil surface estimate methods and to obtain a range of gully cross-sectional areas that should encompass the actual cross-sectional area. The volume of sediment scoured by each debris flow in SCC was calculated from the calculated cross-sectional areas and longitudinal profiles of the gullies. The gully width-to-depth ratio was calculated at each cross-section measurement location using the maximum width and mean depth values (Heede, 1976; Miller and Benda, 2000). Gully depth values near the banks of steep-sided gullies (e.g. depth values <0.10 m) do not represent debris flow scour and were not included in the mean depth calculation.
3. Results

3.1 Field Observations

Rill networks are present above the gully heads of the six SCC debris flow-scoured gullies studied. The rills are 1 to 4 cm deep and converge at the gully heads. The rills are characterized by gravel and cobble stacks collected behind trees, the presence of imbricated cobbles, nick marks on trees, and occasional small levees. Rill networks are often discontinuous and the location of rill initiation is difficult to pinpoint. The accuracy of the rill initiation locations is approximately 10 m. No landslide scarps are present at the gully head locations. The gully heads are steep and cliff-like (Figure 2.2). The steep gully heads may be due to gully head-cutting after the initial incision process. The location of rills and gully heads are shown on the longitudinal profiles of the SCC gullies (Figures 2.4 through 2.9). The majority of the gullies are continuous downslope of the gully head. The exceptions are the 1st fork of debris flow #1 (Figure 2.4) and the fork of debris flow #4 (Figure 2.7). These discontinuous gullies are present where the slope gradient decreases downslope of the gully head. Debris flow deposition occurs with decreased slope gradient and incision continues with increased slope gradient. The debris flow deposition is characterized by lack of channel incision, cobble stacks behind trees, imbricated cobbles, and small levees. The main gully of debris flow #5 has slight incision initially and then is incised deeper approximately 40 meters downslope of the gully head (Figure 2.8). The deepened incision for debris flow #5 occurred at an increase in slope gradient.

Debris flow scour in SCC is characterized by the following evidence: mud coatings and nick marks on the upslope side of adjacent trees and cobbles nested in crooks of
trees. Mud coating, nick marks, and nested cobbles occurred up to 2.5 meters above the ground surface for some of the debris flows. In addition, debris flow scour is characterized by imbricated cobbles and boulders, log and boulder jams, and levees. The levees were typically located in the lower fourth of the gullies (Figures 2.4 through 2.9). Levee height ranged from 0.25 to 2 m.

The debris flows deposited fans on the floodplain and in the channel of SCC, where the valley gradient ranged from 2 to 7 % (Hoffman and Gabet, 2006). Many of the debris flow fans collided with the opposite valley hillslope temporarily damming the creek. The debris flow fans are composed of a mix of matrix-supported sand, gravel, cobbles, and boulders. The matrix is comprised of clays, silts, and vegetative ash.

3.2 Debris Flow Gully Surveys

The longitudinal profiles for the debris flow-scoured gullies are shown in Figures 2.4 through 2.9. These profiles illustrate the steep slope of the SCC gullies, the presence of tributary gullies, and the location of debris flow levees and gully heads. The gully maximum width ranged from 0.7 to 12.7 m. The gully mean depth ranged from 0.3 to 2.7 m. The mean width-to-depth ratios for the SCC debris flow-scoured gullies and gully tributaries range from 2.3 to 5.7 (Table 2.1). The gully width-to-depth ratio data indicate a general trend of increasing width-to-depth ratio with distance downslope (Figure 2.10). The gully depth is typically limited by bedrock; hence increasing debris flow volume is accommodated by increases in gully width. The exceptions to this trend are debris flow-scoured gullies #1 and #2 (Figure 2.10). The lack of downslope width-to-depth ratio increase in these gullies is due to bedrock outcrops that bound the gullies and limited the lateral erosion of the debris flows.
Rill initiation upslope of the debris flow-scoured gullies is located between 31 and 341 m from the basin divide (Table 2.1). The gully heads are located between 105 and 445 m from the ridge crest (Table 2.1). The distance of rill initiation and the gully head below the basin divide are compared to the slope gradient along the axis of the colluvial hollows. The colluvial hollow slope values are measured between 40-foot contours on the USGS Bald Top Mountain Quadrangle, 1:24 000 topographic map. The relationship between rill initiation and the slope gradient at the location of rill initiation suggests a slope-distance threshold for rill initiation (Figure 2.11). The relationship between gully head location and the slope gradient at the gully head suggests a slope-distance threshold for debris flow gully incision (Figure 2.12).

The gully source area and scour volume are evaluated in relationship to the colluvial hollow slope gradient at the gully head. The source area is defined as the drainage area upslope of the gully head. The source area for each debris flow-scoured gully was measured from a 30-meter digital elevation model (DEM) of the field site using ArcGIS 9.0 software. The data suggest a general trend of smaller gully source area with increasing slope at the gully head (Figure 2.13). There is also a general trend of decreasing gully scour volume (see section 2.2.2) with increasing slope at the gully head (Figure 2.14). In addition, the mean gully cross-sectional area tends to decrease with increasing slope at the gully head (Figure 2.15). Furthermore, the gully scour volume is positively correlated to the total gully length (Figure 2.16) and the mean cross-sectional area (Figure 2.17), indicating that debris flows bulk with distance downslope and consequently erode wider gullies. The mean gully expansion rate of the SCC debris...
flow-scoured gullies is 0.006 ± 0.002 m²/m (Figure 2.18). There was no relationship between gully expansion and the mean gully slope gradient.

4. Discussion

The role of fire appears to be critical to debris flow initiation in the Sleeping Child Creek basin. Wildfires increased overland flow and vegetative ash from the fires may have led to progressive bulking of overland flow and subsequent debris flow initiation. Sandy soils typically have high infiltration rates that limit the generation of overland flow. The extensive rill networks present in the source area of the SCC debris flow-scoured gullies indicate that overland flow was pervasive after the fire. Decreased soil infiltration after wildfires may be due to soil hydrophobicity (DeBano, 1981; Huffman et al., 2001; Martin and Moody, 2001) and surface-sealing due to swelling of vegetative ash in the soil pores (Etiegni and Campbell, 1991). In addition, entrained vegetative ash may alter the physical properties of debris flows by decreasing the settling velocity of entrained sediment. Laboratory studies (e.g., Cao and Qian, 1990; Julien and Lan, 1991; Major and Pierson, 1992) indicate that the presence of fines (<2 mm size fraction) can increase the viscosity of sediment slurries, hence decreasing the fall velocity of entrained sediments. Higher flow viscosity and lower fall velocities may allow increased sediment entrainment. This process may work as a positive feedback loop, whereby entrainment of ash increases the capacity of overland flow sediment bulking and debris flow initiation. Cannon et al. (2001) also found the presence of vegetative ash to be critical to the initiation of debris flows after the Cerro Grande fire, New Mexico. The debris flow deposits in the SCC basin contained vegetative ash in the fine-grained matrix indicating that vegetative ash played a role in the SCC debris flows.
The slope-area thresholds indicate that overland flow generated the SCC debris flows. The shear stress at the slope-area threshold is equal to the boundary shear stress that will incise channels and is defined in the following equation.

$$\tau_0 = \rho g h S \quad [1]$$

Where $\tau_0$ is the boundary shear stress, $\rho$ is the density of the water, $g$ is the acceleration of gravity, $h$ is the flow depth, and $S$ is the slope gradient. The drainage area or the distance below the basin divide can be used as a proxy for the flow depth. The boundary shear stress, then, is proportional to the product of the slope gradient and the source area ($A_d$) or distance below the basin divide ($x_c$) as shown in the following equations.

$$\tau_0 \propto A_d S \quad [2]$$

$$\tau_0 \propto x_c S \quad [3]$$

Slope-area thresholds represent a zone of transition between channeled and unchanneled hillslope regions (Montgomery and Dietrich, 1994). The erosional shear stress above a slope-area threshold is inadequate to overcome soil resistive forces and incise channels. Montgomery and Dietrich (1994) combined the theoretical slope-area thresholds of diffusive, seepage, landslide, and overland flow erosion processes to define landscape regions where the different erosion and channel initiation processes dominate. The slope-area thresholds for the SCC debris-flow scoured gullies (Figures 2.11 and 2.12) match the theoretical and empirical slope-area thresholds for overland flow (Montgomery and Dietrich, 1994, pp. 235). This close match of slope-area thresholds indicates that channel initiation in the SCC basin occurred due to overland flow. In addition, the debris flows in SCC cannot be attributed to landslides, which is the predominant mechanism for debris flow initiation (Iverson et al., 1997). The rill networks, absence of landslide
scarps, and slope-area thresholds in SCC indicate that the debris flows in SCC were initiated by overland flow. Extensive overland flow evidence (e.g. rilling) in SCC suggests that little runoff was infiltrating into the soil a necessary precursor to landsliding (Iverson et al., 1997).

There is substantial variability between the different SCC debris flow-scoured gully morphometric parameters (e.g., gully head locations, slope-area thresholds, scour volume, etc.). This variability can be attributed to several natural variables. The morphology of source area above gully heads varies. The type and density of vegetation varies. Rainfall intensity will also vary within steep, high-relief basins. Fire severity will vary due to fuel availability, weather conditions, and hill slope gradient and aspect. These natural variables can influence many different debris flow initiation and morphology parameters. Source area morphology and rainfall intensity will impact the quantity of overland flow and sediment erosion. Fire severity and vegetation variations may impact the amount and spatial continuity of soil hydrophobicity, which may affect soil infiltration and soil disaggregation (e.g., Mataix-Solera and Doerr, 2004; Moody et al., 2005). Variations in soil hydrophobicity may result in variations in the quantity of overland flow and soil erosion. The above natural variations may impact the location of rill initiation and gully heads, the slope gradient at the gully heads, and the debris flow volume.

The long-term geomorphologic evolution of hillslopes and landscapes are significantly impacted by wildfire and debris flows. The geomorphic evolution of colluvial hollows has been described as a complex interaction of sediment deposition and erosion (Reneau et al., 1990). Hollows fill over periods of thousands to tens of thousands
of years (Reneau et al., 1990) by soil creep processes including bioturbation (Gabet et al.,
2003) and dry ravel (Wells, 1987; Gabet, 2003). The colluvium is subsequently
excavated by landslides and debris flows (Reneau et al., 1990). The debris flow-scoured
gullies in the SCC basin indicate that wildfires followed by intense rainfall and debris
flows can greatly increase colluvial sediment excavation. The excavation of hillslope
colluvial hollows can lead to extensive stream aggradation (Reneau et al., 1990).
Hollows almost immediately begin refilling and the infilling processes are accelerated
after wildfires due to lack of vegetation (Cannon and Reneau, 2000), increased soil
erodibility (DeBano, 1981; Neary et al., 1999), burnt tree dead fall (Gabet et al., 2003),
and erosion of gully banks. The SCC gullies have already partially infilled between the
2001 gully rejuvenation and the 2005 surveys (Figure 2.3). The greatest gully infilling
was a result of tree fall and gully bank erosion. The above hillslope evolution process
will repeat itself. High frequency, low magnitude soil creep will load colluvial hollows
and then be emptied catastrophically by post-wildfire debris flows. In addition, the
colluvial hollow bed elevation may be lowered due to bedrock erosion by debris flows
(Stock and Dietrich, 2003). Debris flow erosion of colluvial hollow bedrock can control
valley dissection and mountain elevation in steep gradient headwater streams (Stock and
Dietrich, 2003).
5. **Conclusions**

The post-wildfire debris flows in SCC were initiated by progressive sediment bulking, not landslides. Evidence for progressive bulking, rather than landslides, include: the absence of landslide scarps, the presence of rill networks, and slope-area thresholds that suggest that overland flow was prevalent. The evidence of overland flow indicates a lack of soil saturation, which decreases the possibility of landslides. In addition, the debris flow-scoured gullies enlarge with downslope distance. The mean debris flow-scoured gully expansion rate in SCC is \(0.006 \pm 0.002 \text{ m}^2/\text{m}\). The gully expansion does vary between the debris-flow scoured gullies and has a poor linear relation for some of the gullies. The SCC debris flow-scoured gullies are characterized by steep gully heads, generally continuous gullies, mud coating and nick marks on adjacent trees, log and boulder jams, and levees in the lower portion of the gullies.

Post-wildfire debris flows are important geomorphic agents. The debris flow-scoured gullies in the SCC basin support cyclic landscape evolution models of colluvial hollow deposition and excavation. This process can be accelerated by wildfires, which increase soil creep deposition and magnify debris flow excavation. In addition, post-wildfire debris flows may control valley morphology through bedrock erosion and sediment inputs to stream channels.

6. **Acknowledgements**

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7. References


Figure 2.1. Location of Sleeping Child Creek basin in southwest Montana. (A) Sleeping Child Creek basin boundary. (B) Inset of debris flow study area. White triangles denote debris flow-scoured gully heads.
Figure 2.2. Photograph of debris flow-scoured gully head in Sleeping Child creek, southwest Montana. The photo is looking upslope. The gully is approximately 1.0 m deep and 1.5 m wide. Note the steep gully head (background), cobble jam (foreground), and burnt trees.
Figure 2.3. Photograph of debris flow-scoured gully in Sleeping Child creek, southwest Montana. The photo is looking downslope. The gully is approximately 1.5 m deep and 2.5 m wide. Note the levee on the right-hand side, the cobble stacks behind the trees, the mud-coating on the near right-hand side tree, partial gully infilling, and the burnt trees.
Figure 2.4. Longitudinal profile for Sleeping Child Creek debris flow-scoured gully #1. Solid lines indicate incised channels, dotted lines indicate rill networks that are not incised, and asterisks (*) represent gully head locations. The longitudinal profiles of Fork #1 and Fork #2 are vertically offset by 5 and 15 meters, respectively, to obtain a clear representation.
Figure 2.5. Longitudinal profile for Sleeping Child Creek debris flow-scoured gully #2. Solid lines indicate incised channels, dotted lines indicate rill networks that are not incised, and asterisks (*) represent gully head locations. The longitudinal profiles of the Fork is vertically offset by 10 meters to obtain a clear representation.
Figure 2.6. Longitudinal profile for Sleeping Child Creek debris flow-scoured gully #3. Solid lines indicate incised channels, dotted lines indicate rill networks that are not incised, and asterisks (*) represent gully head locations.
Figure 2.7. Longitudinal profile for Sleeping Child Creek debris flow-scoured gully #4. Solid lines indicate incised channels, dotted lines indicate rill networks that are not incised, and asterisks (*) represent gully head locations. The longitudinal profile of the Fork is vertically offset by 20 meters to obtain a clear representation.
Figure 2.8. Longitudinal profile for Sleeping Child Creek debris flow-scoured gully #5. Solid lines indicate incised channels, dotted lines indicate rill networks that are not incised, and asterisks (*) represent gully head locations. The asterisk with the arrow above it represents further incision at a rill network confluence.
Figure 2.9. Longitudinal profile for Sleeping Child Creek debris flow-scoured gully #6. Solid lines indicate incised channels, dotted lines indicate rill networks that are not incised, and asterisks (*) represent gully head locations.
Figure 2.10. Plot of gully length and width-to-depth ratio debris flow-scoured gullies in the Sleeping Child creek basin, southwest Montana. The width-to-depth ratio generally increases with downslope.
Figure 2.11. Plot of the distance of rill initiation below the ridge crest and the slope at the location of rill initiation for debris flow-scoured gullies (n = 13) in Sleeping Child creek, southwest Montana. The grey dashed line represents the threshold between channeled and unchanneled portions of the landscape. The data indicate an inverse relationship between the distance of rill initiation below the ridge crest and the slope at the location of rill initiation.
Figure 2.12. Plot of the distance of the gully head below the ridge crest and the slope at the gully head for debris flow-scoured gullies (n = 14) in Sleeping Child creek, southwest Montana. The grey dashed line represents the threshold between channeled and unchanneled portions of the landscape.
Figure 2.13. Plot of the gully source area (km$^2$) and the slope at the gully head for debris flow-scoured gullies (n = 12) in Sleeping Child creek, southwest Montana. The data indicate an inverse relationship between the source area and the slope at the gully head. The grey dashed line represents the threshold between channeled and unchanneled portions of the landscape.
Figure 2.14. Plot of the median gully scour volume estimate ($m^3$) and the slope at the gully head for debris flow-scoured gullies in Sleeping Child creek, southwest Montana. The solid line is a linear best fit line of the data. The data indicate an inverse relationship between the gully scour volume and the slope at the gully head.
Figure 2.15. Plot of the mean gully cross-sectional area (m²) and the slope at the gully head for debris flow-scoured gullies in Sleeping Child creek, southwest Montana. The gully cross-sectional area is calculated from the median estimate of the original soil surface in the colluvial hollow. The solid line is a linear best fit line of the data. The data indicate an inverse cross-sectional area and gully head slope relationship.
Figure 2.16. Plot of the median gully scour volume estimate (m$^3$) and the total length of debris flow-scoured gullies in Sleeping Child creek, southwest Montana. The solid line is a linear best fit line of the data. The data indicate a linear increase in scour volume with longer gullies.
Figure 2.17. Plot of the gully scour volume estimate (m$^3$) and the mean cross-sectional area (m$^2$) of the debris flow-scoured gullies in Sleeping Child creek, southwest Montana. Both the scour volume and cross-sectional area values were calculated using the median original soil surface. The solid line is a linear best fit line of the data. The data indicate a linear increase in scour volume with larger gully cross-sectional area.
Figure 2.18. Representative plot of the total gully length versus the mean cross-sectional area (m²) for debris flow-scoured gully #5 in Sleeping Child creek (SCC), southwest Montana. The R² values ranged from 0.26 to 0.91 for the six SCC gullies. The gully cross-sectional area is calculated from the median estimate of the original soil surface. The solid line is a linear best fit line of the data. The slope of the linear best fit line is the gully expansion rate (dA/dx), which is 0.0054 m²/m for gully #5.
Table 2.1 - Debris flow-scoured gully properties in the Sleeping Child creek basin, southwest Montana.

<table>
<thead>
<tr>
<th>Debris Flow</th>
<th>Gully Head Drainage Area (km²)</th>
<th>Total Scour Volume (m³)</th>
<th>Distance from Ridge to Gully Head (m)</th>
<th>Slope at Gully Head (%)</th>
<th>Distance from Ridge to Rill Initiation (m)</th>
<th>Slope at Rill Initiation (%)</th>
<th>Mean Width-to-Depth Ratio</th>
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<tr>
<td></td>
<td></td>
<td>Low</td>
<td>Mid</td>
<td>High</td>
<td>Distance from Ridge to Gully Head</td>
<td>Slope at Gully Head</td>
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<td>370</td>
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<td>48</td>
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<td>---</td>
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<td>574</td>
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ND = not determined