Characterization of a Runoff-initiated Post-fire Debris Flow in the Western Cascades, Oregon: Implications for high severity fire in the Pacific Northwest

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ABSTRACT

Wildfires dramatically alter the hydrologic response of soil in forested hillslopes, which can result in the generation of debris flows. Two types of debris flows occur in response to wildfire, namely debris flows initiated via shallow landsliding and debris flows initiated by runoff and debris entrainment. In the Pacific Northwest, post-fire shallow landsliding has been well documented and studied, but the potential role of runoff-initiated debris flows is not well understood and no post-fire runoff-initiated debris flows have been documented in this region. On June 20th, 2018, approximately one-year after the Milli fire burned 24,000 acres, a post-fire runoff-initiated debris flow occurred on the flanks of Black Crater in the high Cascades in Oregon. High fire severities that occurred during the Milli fire resulted in dramatically reduced soil infiltration rates at the study site, as measured in the field with a mini-disk infiltrometer. We quantified rainfall rates for the storm event that triggered the debris flow, finding that peak 15-minute rainfall rates were 25.4 mmh$^{-1}$, exceeding the measured infiltration rates at the study site, which had a geometric mean between 24.64 mmh$^{-1}$ and 24.9 mmh$^{-1}$ depending on soil texture. Field mapping shows that the combination of high fire severity and topography contributed to the occurrence of a debris flow initiated by runoff at this site. As wildfires increase in frequency and intensity across the western United States, the Pacific Northwest could become more susceptible to runoff-initiated debris flows. Therefore, understanding the conditions that resulted in this debris flow on Black Crater is necessary in understanding how runoff-initiated debris flows operate in the Pacific Northwest.

Keywords: Post-fire debris flow, Post-fire runoff, Wildfire, Oregon Cascades, Soil Infiltration, Climate Change
INTRODUCTION

As wildfires increase in frequency and intensity across the Western United States, it is necessary to understand their fundamental impacts on hydrologic response and erosion. Post-fire debris flows are one of the most destructive consequences from wildfire’s alteration of the soil in mountainous landscapes. There are two primary processes for the initiation of post-fire debris flows: debris flows resulting from soil saturation and shallow landsliding and runoff-initiated debris flows that mobilize from rainfall rates exceeding post-fire reduced infiltration rates (Cannon and Gartner, 2005; Parise and Cannon, 2012). Runoff-initiated debris flows are a common response to high-intensity rainfall on burned hillslopes in Mediterranean climates (Inbar et al., 1998; Wondzell and King, 2003; Kampf et al., 2016). In the United States, such debris flows have been documented in Southern California, the Rocky Mountains, and Interior Northwest, which includes parts of Eastern Oregon and Idaho, and have resulted in catastrophic loss of life and homes (Cannon and Gartner, 2005; Wondzell and King, 2003, Jordan and Covert, 2009; Gartner et al., in press). While across the American West runoff-initiated debris flows are the primary geomorphic response to fire, they have not been reported in the Pacific Northwest (Wondzell and King, 2003; Cannon and Gartner, 2005; Parise and Cannon, 2012). Rather, by contrast, shallow landslides initiated via soil saturation and weakened root structures are the predominant geomorphic response to fire observed in this region (Ziemer and Swanston, 1977; McNabb and Swanson, 1990; Montgomery and Dietrich, 1994; Schmidt et al, 2001, Jackson and Roering; 2009; Lanini et al., 2009).
Runoff-initiated debris flows occur because wildfires dramatically reduce the infiltration capacity of the soil, which can be attributed to numerous processes. Vegetation, organic matter, and organic rich soil horizons that protect the mineral soil from rain splash are incinerated during fire (Larsen et al., 2009; Parise and Cannon, 2012; Robichaud et al., 2016). This leaves fine particulates of the mineral soil unprotected and prone to washing into aggregates and pores in the soil structure, sealing soil surfaces off from rain infiltration (Meyer and Wells, 1997; Cannon et al, 2001; Robichaud et al., 2016). In addition, organic matter that holds soil aggregates together (Tisdall and Oades, 1982; Roldan et al., 1994) is combusted by fire, causing aggregates to collapse, which clogs pores in the soil that previously enabled infiltration, further sealing the soil’s surface (Swanson, 1981; Mataix-Solera and Cerda, 2009; Mataix-Solera et al., 2011). Lastly, incineration of organic matter by wildfire can form hydrophobic compounds that create a hydrophobic layer in the soil, which works to repel water (Dryness, 1976; DeBano, 1981; Doerr et al., 2000; Cannon, 2001; Huffman et al, 2001; Doerr et al., 2009). Hydrophobic layers have been observed to last up to six years after wildfires (Dryness, 1976). However, some studies have found that increased soil moisture reduces the effectiveness of hydrophobic layers (Wells et al., 1979) and that hydrophobicity relies on vegetation type and soil texture (Dryness, 1976; DeBano et al., 1998; Robichaud and Hungerford, 2000).

Because runoff-initiated debris flows occur in response to immediate post-fire reduction in soil infiltration rates, they can be triggered by the next large storm following a fire, which can be a timeframe of days to weeks after a fire (Wondzell and King, 2003; Cannon et al., 2008). The majority of runoff-initiated debris flows occur within two years
after a fire and greatly reduce in likelihood with more time out as vegetation regenerates and hydrophobicity decreases (Santi and Morandi, 2013; Vieira et al., 2015; Gartner et al., in press).

The initiation of debris flows via runoff is determined by high fire severities that dramatically alter the infiltration capacity of soil and high-intensity rain falling on these burned hillslopes, which results in rill and sheetwash erosion (Neary et al., 2010; Vieira et al., 2015; Gould et al., 2016). The transition between rilling and sheetwash into a debris flow relies heavily on topographic influences such as slope steepness, convergence on the hillslope, and channel incision (Meyer and Wells, 1997; Cannon et al., 2001). Hillslope erosion has been observed to contribute the majority of transported sediment to the debris flows via shallow erosional networks (Rengers et al., 2016). Topographic convergence consolidates entrained sediments, which results in deeper erosional features and transports large amounts of material downslope (Cannon and Gartner, 2005; Rengers et al., 2016).

The hazard and destructive potential of a debris flow comes from a debris flow’s ability to entrain increasing amounts of sediment moving downslope (Hungr et al., 2005). The hazard of a debris flow event can be understood by the volume of material transported during the event because the amount of sediment transported influences travel speeds, inundation area, momentum of flow, and runout potential (Iverson et al., 2011). To predict the associated hazard of a burned basin, the US Geologic Survey constructed a model that considers both the probability for a debris flow to occur in a burned basin and the predicted volume of deposit for the given basin (Staley, 2013). Estimating the
probability of debris flow is based on variables such as fire severity, slope of basin, and soil characteristics. Basin volume predictions are dependent on variables such as fire severity of the basin and topographic convergence. The most hazardous basins, according to the USGS model, show high probability of occurrence and a large estimated volume of deposit.

Debris flows initiated by soil saturation and shallow landslides occur when post-fire tree mortality results in root strength decline (Burroughs and Thomas, 1977; Jackson and Roering, 2009). Tree roots increase soil stability on steep slopes (Ziemer and Swanston, 1977). In environments where root strength is impaired, such as after a fire, resisting forces on the hillslope are unable to resist the driving forces of soil, especially after heavy rainfall and subsequent soil saturation. When driving forces such as slope steepness, increased soil pore pressure, soil thickness, and physical properties of the soil exceed the resisting forces of damaged tree roots, shallow landslides occur (Cannon and Gartner, 2005; Parise and Cannon, 2012). Landslide failures observed in burned areas in the literature range in thickness between centimeters to over 6 meters thick and they leave a clear landslide scar at the source area from which they mobilize (Cannon and Gartner, 2005). Jackson and Roering (2009) found that there is progressive root strength decline after fire, resulting in debris flows via soil saturation becoming more likely in successive years following fire (Burroughs and Thomas, 1977; May and Gresswell, 2003; Gorsevski et al., 2006).

In the Pacific Northwest, there has been an emphasis on studying post-fire debris flows that result from shallow landslides (Woodsmith, 2009; Jackson and Roering, 2009; Lanini et al., 2009), but the role of runoff-initiated debris flows in the region is not
clearly understood. Wondzell and King (2003) suggest that runoff-initiated debris flows have only been documented in the Rocky Mountains, Interior Northwest, and Southern California because of the prevalence of high-intensity, short-duration rainfall in these regions, which is necessary for the initiation process of such debris flows (Kampf et al., 2016; Gartner et al, in press). Increased runoff after fire results from rainfall intensity exceeding the soil infiltration rates, which is greatly impacted by rainfall rate during a storm event and the saturated hydraulic conductivity of the soil (Ebel and moody, 2016; McGuire et al., 2018).

In the Pacific Northwest, long-duration, low-intensity rainfall paired with notably high soil infiltration rates makes the occurrence of runoff-initiated debris flows unlikely (Dryness, 1969; Harr, 1977; McNabb et al, 1989; Schmidt, 1995). Additionally, the effectiveness of hydrophobicity decreases with increased soil moisture (Wells et al., 1979). Therefore, in the Pacific Northwest’s wet climate, even large storm events typically do not result in runoff-initiated debris flows because they often fall on already wet soils where the effects of hydrophobicity are negligible. Vegetative types also vary between the Pacific Northwest and Interior Regions. Wondzell and King (2003) speculate that the rapid regeneration of vegetation after fire in the Pacific Northwest decreases the likelihood of runoff-initiated debris flows and results.

On June 20th, 2018, a runoff-initiated debris flow occurred in the Western Cascades in Oregon on the northwest flank of Black Crater. The debris flow occurred in a region that had burned one year prior in the Milli Fire during the summer of 2017. This is the first reported case of a runoff-initiated debris flow occurring in the Pacific Northwest. We identified this debris flow, the Milli Debris Flow (MDF), to be initiated by surface
runoff due to the observation of rills and sheetwash as the source of the flow rather than a shallow landslide (Wells, 1987; Spittler 1995; Cannon et al, 2001).

The objective of this paper is to offer an in-depth characterization of this post-fire debris flow and to explore the conditions that facilitated this process to occur in the Pacific Northwest. As the effects of climate change result in more extreme wildfire events in the Pacific Northwest (Westerling et al., 2006; Gould et al., 2016), this region could become more susceptible to runoff-initiated debris flows. By examining the MDF and understanding the factors that contributed to its initiation, we can better understand the susceptibility of the Pacific Northwest to runoff-initiated debris flows in the future. This paper examines spatial and temporal factors that contributed to the initiation of the MDF, which include topography, fire severity, soil infiltration rates, and rainfall rates from the storm event that resulted in the debris flow.

SETTING

Post-Fire Geomorphic Processes in Western Oregon

Fire-related geomorphic studies in the Pacific Northwest have predominantly focused on dry ravel and debris flows initiated via soil saturation (Mersereau and Dryness, 1972; Helvey, 1980; Roering et al., 2003; Jackson and Roering, 2009). Swanson (1981) concluded that intense wildfires in Western Oregon forests may result in a five-times increase in sediment yield compared to non-burned yield rates. He also found that for a small watershed studied in the Western Cascades, post-fire erosion accounts for 25% of long-term sediment yield (Swanson, 1981). Post-fire erosion rates have been observed to decrease after two years following fire due to the rapid recovery of vegetation after fires in this climate (Mersereau and Dryness, 1972; Wondzell and King,
2003). A study done in the Western Cascades focused on measuring sediment transport downslope after a prescribed burn and found that rates of ravel were reduced to nearly zero by the second growing season post-fire (Mersereau and Dryness, 1972).

Root strength decline after a fire also plays an integral role in post-fire erosion in the Pacific Northwest and contributes to the production of dry ravel and shallow mass wasting events (Burroughs and Thomas, 1977; Roering et al., 2003; Jackson and Roering, 2009). Roering et al. (2003) found that changing variabilities of root-strength observed in the Oregon Coast Range directly relates to hillslope susceptibility for shallow-landsliding.

Hydrophobicity has also been observed in soil following fire in the Pacific Northwest (Dryness, 1976; Johnson and Beschta, 1980; McNabb et al., 1989; Jackson and Roering, 2009). Jackson and Roering (2009) observed patches of strongly hydrophobic soils at majority of their field test sites after fire in the Oregon Coast Range. The hydrophobicity, while extreme in some locations, was highly localized in patches. Post-fire rain events did not result in runoff erosion at their study sites due to the high spatial variability of infiltration rates observed.

Many studies conclude that runoff-initiated debris flows do not occur in the Pacific Northwest because rainfall rates rarely exceed the high soil infiltration rates (McNabb et al, 1989; Schmidt, 1995; Wondzell and King, 2003). Schmidt (1995) found that post-wildfire change in soil infiltration was negligible in a watershed in Southern Oregon for two years following fire due to high infiltration rates. McNabb et al. (1989) measured soil infiltration rates post-fire in the Oregon Coast Range using a mini-disk infiltrometer, finding infiltration rates to be significantly lower for burned soils rather
than unburned, but these rates still exceeded rainfall rates by 2 to 3 times. Montgomery et al. (1997) observed infiltration rates in the Oregon Coast Range that were over 360 mm\textsuperscript{-1}. Another study conducted in the Oregon Coast Range by Montgomery and Dietrich (2002) observed extremely high infiltration rates of 1,332 mm\textsuperscript{-1}.

High infiltration rates have also been observed in the Western Cascades. According to a study done by the US Forest Service (1973), soil infiltration rates at HJ Andrews Experimental Forest in the Western Oregon Cascades on average exceeded 200 mm\textsuperscript{-1}. Another study conducted in the HJ Andrews Experimental Forest by Johnson and Beschta (1981) found average summer infiltration rates to be 80.0 mm\textsuperscript{-1}. Additionally, Johnson and Beschta (1980) found soil infiltration rates in multiple locations in the Western Oregon Cascades to range between 50.8 and 114.3 mm\textsuperscript{-1}. Storms in the Western Oregon Cascades that exceed rainfall rates of 100 mm\textsuperscript{-1} have return intervals of 100 years and such rainfall intensities have not been observed to last longer than 5 minutes (Oregon Department of Transportation, 2014). In the Pacific Northwest, overland flow has rarely been observed because it is unprecedented that low regional rainfall intensities would exceed the high soil infiltration rates characteristic of the region.

**2018 Milli Debris Flow**

The Milli Debris Flow occurred on June 20\textsuperscript{st}, 2018 on the northwest flank of Black Crater (Fig. 1). The debris flow was runoff-initiated, which was determined due to its rill and sheetwash source area. The debris flow began on the upper slopes of Black Crater and followed the localized convergence of the volcano across Highway 242 in two
Figure 1. Map showing location of Black Crater and nearby National Forests and highways. (A) Shows geographic location of study site and the three rain gauges. The yellow triangle shows location of Black Crater, the red dot shows location of HJ Andrews Experimental Forest rain gauge, the orange dot shows the location of Bear Grass SNOTEL rain gauge, and the blue dot shows the location of Smith Ridge SNOTEL rain gauge. (B) Indicates the extent of the 2017 Milli Fire in red. (C) Shows LIDAR of Black Crater and the hashed line area indicates the flank of Black Crater where the MDF occurred.
locations at the toe of the slope. The June 20\textsuperscript{th} storm event that triggered the debris flow experienced peak rainfall rates at 2:25 pm followed by another surge at 4:00 pm.

**Geologic Background and Topography**

The MDF occurred on the northwest flank of Black Crater in the volcanic plateau of Oregon’s High Cascades. Black Crater is a Pleistocene shield volcano consisting almost entirely of olivine basalt and olivine-bearing basaltic andesite (Williams, 1944). Scoria cones have developed on the southwest flank of the volcano and a parasitic lava cone formed close to the western base (Fig. 1). It is an older volcano for the region and was glaciated during the last ice age (Williams, 1944).

While Black Crater’s volcanic activity ended during the early Pleistocene, there are many other younger and more recently active volcanoes in the region. Such volcanoes include Belknap and Little Belknap Crater, which are eight kilometers west of Black Crater’s summit. Belknap Crater most recently erupted 5,570 years ago and likely draped Black Crater in its ashes. Mount Mazama erupted 7,700 years ago, which also likely contributed a blanket of ash to Black Crater’s surface and the surrounding Cascades (Taylor, 1965). The nearby eruptions along with weathering of in situ bedrock has contributed the parent materials of the soils on Black Crater.

The topography of the Oregon High Cascades is characterized by the broad, conical shapes of stratovolcanoes on top of the undulating volcanic plateau. The debris flow occurred on Black Crater, which has the broad conical shape of a shield volcano, yet convergence does exist locally on its slopes from minor channel incisions and stream network development (Fig. 2). Many volcanoes in the region are bare of soil and vegetation due to their steep slopes, high elevations above tree line, or recent and exposed
Figure 2. Northwest flank of Black Crater, purple denotes the area that contributes to the channel networks and the blue lines indicate where water convergence exists on the volcano as determined through GUS analysis of the topography. The perimeter of the debris flow is layered on top of the GIS analysis for expected convergence and flow paths.
lava flows. In contrast, Black Crater is completely forested and has an average steepness between 11 and 20 degrees. Black Crater’s summit is at an elevation of 7,257 ft and the mountain has a relief of 1,850 feet.

**Climate, Vegetation, and Soils**

The annual precipitation in the Oregon Cascades is 3.5–4 meters and the climate is characterized by long-duration, low-intensity rainfall, resulting in soil infiltration rates that are infrequently exceeded even after intense fire (Wondzell and King, 2003). Rapid regeneration of vegetation is characteristic of this wet climate, which further reduces the likelihood of runoff-initiated debris flows. East of the Cascades, precipitation declines to less than 0.4 meters within 30 km east of the range. Black Crater is positioned in the center of this cascade divide and climatic transition. The eastern side of the mountain is vegetated by Ponderosa Pine (*Pinus ponderosa*) and Bitterbrush (*Purshia tridentata*) woodland. The western flank of Black Crater is vegetated by Cascade Crest Montane Forest, which is dominated by mountain hemlock (*Tsuga mertensiana*) and pacific silver fir (*Abies alba*). The MDF moved west through the Cascade Crest Montane Forest on Black Crater’s Northwest slope. The soils on Black Crater are andisols that are very fine-grained sandy loam and loamy sand. Tephra layers are present in the soil from nearby volcanic activity.

**Western Oregon Fire Regime and the 2017 Milli Fire**

In the Western Cascades, the mean fire return interval between 1480 and the early 20th century for high-severity complete stand-replacing fires was 166 years and for all fires was 114 years (Teensma, 1987). A study done in the Siskiyou Mountains of the Oregon Coast Range, found that over millennia, fire was more episodic than observed
today and was characterized in this region by mean fire intervals between 52 and 180-years (Colombaroli and Gavin, 2010). On the Eastern side of the Cascades, the historical fire regimes were characterized by fire return intervals between 5 and 35 years with mixed severities (Agee, 2003). Over the first half of the 20th century, all fires on public lands were suppressed, which has resulted in an increased fuel load in western forests today.

Due to climate change, fire seasons in the Western U.S. are projected to become longer and drier, resulting in higher intensity fires occurring with more frequency (Westerling et al., 2006; Wimberly and Liu, 2014; Gould et al., 2016). A study conducted by Wimberly and Liu (2014) found that the mean annual temperature change by the 2080s is to increase between 2.5 to 3.5 degrees Celsius depending on different emission scenarios. Due to the warming climate and changing fire seasons, Wimberly and Liu (2014) also have found that today in the Pacific Northwest, the burned area per fire season is 76 to 310% greater than historical amounts and that this is projected to continue to increase in the Western Cascades (Gould et al., 2016). Under future, warmer climates the Western Cascades and their fire regime will be particularly influenced by climate change (Gould et al., 2016; Wimberly and Liu, 2014).

Increased fuel loads due to fire suppression legacies in western forests in combination with lengthening and higher-intensity fire seasons in the Pacific Northwest have resulted in more extreme fire seasons in this region than reported previously (Stephens and Ruth, 2005). The 2017 fire season in Oregon was marked by extreme fire behavior of multiple large, long-duration fires and has been recognized as the worst, and one of the longest, fire seasons on record (U.S. Forest Service, 2017; Oregon Forest
Resources Institute, 2018). The month of July had temperatures well above average across the Western United States and the month of August was the hottest on record in Oregon and Washington (U.S. Forest Service, 2017). The average fire season in Oregon has grown by 78 days since the 1970’s and in 2017, 665,000 acres of forests and rangeland burned in over 2,000 fires across the state (Oregon Forest Resources Institute, 2018).

The MDF occurred on June 20th, 2018 in the burn scar of the Milli Fire on the northwest flank of Black Crater (Fig. 1). The Milli Fire began from a lightning strike on August 11th in the Three Sisters Wilderness Area within the fire boundary of the 2006 Black Crater Fire. The fire then expanded into unburned fuel north of the boundary of the 2012 Pole Creek Fire and south of the 2006 Black Crater Fire. The Milli Fire grew to be over 24,000 acres, resulted in the evacuation of homes in the area, and eventually was contained on September 24th, 2017 (U.S. Forest Service, 2017).

The Burn Area Emergency Response team reported that the Milli Fire had one of the highest soil burn severities of the Oregon fires that year with 27% of the area rated at moderate-high severities. Patches of severely burned soil were present at Black Crater and were identifiable by their reddish-orange color. Further, 40% of the fire acres had greater than 50% overstory mortality, which further indicates a high severity fire (U.S. Geological Survey, 2017).

In 2018, the first summer after the Milli Fire, revegetation was scarce to non-existent on the landscape. The soil was exposed, mixed with ash, charcoal, and pine needles. The burnt soil was very fine-grained and dark grey in color. On the flank of Black Crater where the MDF had occurred, 34% of the area was burned at moderate
severity, 41% was burned at moderately-high severity, and 22% was burned at high-
severity (U.S. Geological Survey, 2017; Fig. 3).

**USGS Post-Fire-Debris-Flow Hazard Assessment of 2017 Milli Fire**

The USGS hazard assessment relies upon empirical models that estimate the
probability of occurrence and volume of debris flow for selected burned basins in
response to set rainfall rates (Staley et al., 2017). The model predicts likelihood of debris
flow, volume of deposit, and combined hazard for drainage-basins affected by fire. The
probability model is based upon a logistic regression approach that incorporates variables
such as: proportion of upslope area in burned area that burned at moderate to high
severities with gradients over 23 degrees, the average normalized burn ratio of upslope
area, and soil texture characteristics such as the erodibility factor (Staley, 2013; Staley et.
al, 2017). The volume model is predicted using a multiple linear regression model. The
variables considered in this model are the range of elevation values within the upstream
watershed of a basin, the area upstream that was burned at moderate-high severities, and
designated rainfall intensities. The probability and volume models are cumulated to
define combined relative-hazard for basins during different rainfall conditions (Staley,
2013).

On Black Crater, majority of the basin probability for generating a debris flow
ranged between 0-40% and one basin on the eastern flank of the mountain was assessed
to have a 40-60% probability of generating a debris flow. On the northwest flank of
Black Crater where the MDF occurred, the basin probability of a debris flow was
between 20-40%. The basin volume prediction on the northwest flank of the volcano
ranged between less than 1000 m$^3$ to up to 100,000 m$^3$, although majority of this area was
Figure 3. (A) is a map of fire severity overlain by the MDF perimeter. Bar graph shoes distribution of fire severities on the flank of Black Crater where the debris flow occurred. (B) is a map of slope steepness overlain by the MDF perimeter. Bar graph shows the distribution of slope steepness on the flank of Black Crater where the debris flow occurred. Both maps show location of infiltrometer sites and features of the MDF.
predicted to have volumes of deposit that ranged between 10,000 to 100,000 m$^3$ (Fig. 4). Majority of Black Crater was classified as having a “moderate” combined hazard. Nowhere on Black Crater was designated as having a “high” combined hazard (U.S. Geological Survey, 2017).

METHODS

Mapping

To understand spatial factors that contributed to the occurrence of the MDF, I mapped the debris flow. This entailed walking the entire perimeter of the flow and recording GPS points along the way (Fig. 5). At each GPS point I wrote down if the section of flow was deposition, erosional, or source area. Additionally, at each erosional and source area point I measured and recorded the depths of erosional features. From these data I created maps of the debris flow and features using ArcMap. I was able to use GIS to analyze spatial relationships between debris flow features and the slope steepness and fire severity of the basin where the MDF occurred.

Because the volume of material transported during a debris flow dictates the run out potential and hazard of the flow, I mapped and measured the volume of the depositional area. To measure the sediment volume in the depositional area I used a metal rod of a known length, pushed it vertically into the deposition until there was resistance, marking the lower limit of the deposit, and then measured the length of the rod above the surface. From this I was able to calculate the height of the deposition across the area. In total, I took 23 different measurements of the deposition. Through simple volume calculations I was then able to calculate a rough estimate for the volume of the deposition.
Figure 4. USGS Hazard Assessment for the 2017 Milli Fire on Black Crater. Perimeter of MDF is overlaid on top of hazard analysis. (A) shows basin probability for debris flow to occur, (B) shows the volume prediction for amount of material transported from the basin, and (C) shows the combined hazard analysis which considers both A and B.
Figure 5. (A) shows each GPS point marked during the mapping process, which is denoted by red dots and numbered labels. The yellow line is the track that we walked around the perimeter of the flow. (B) shows a mini-disk infiltrometer at the field site. We cleared away pine needles for the mini-disk to make full contact with the soil’s surface.
Soil Infiltration Rates

To find the soil infiltration rates for the study site, I followed the field methods of McGuire et al. (2018). I used a mini-disk infiltrometer to measure soil surface saturated hydraulic conductivity (Fig. 5). I filled the mini-disk infiltrometer with water, placed it on the surface of the soil in areas that had been burned but not affected by the debris flow, and recorded the volume of water in the cylinder at time intervals of 30 seconds. I conducted a total of 34 measurements at 7 different locations along the debris flow (Fig. 3). Each location was chosen because it was within or next to the perimeter of the debris flow, but its surface had not been eroded or affected by the flow.

Four of the sites (1, 2, 3, 5) were located on the perimeter of the source area for the flow and were on soils that had been burned at moderately-high to high severities (Fig. 3). The surface cover at sites 1 and 2 were predominantly pine needles, both burned and not burned. At site 3 the surface had no cover and was composed of a fine-grained, sandy soil. Because of the surface material’s resemblance to the debris flow’s deposit, site 3 could be an isolated patch of deposition and therefore was deemed unreliable. Site 5 had a surface cover of pine needles and was located on the edge of a levee outside of the flow’s perimeter. Three of the sites (4, 7, 8) were located in or along the erosional section of the debris flow in areas that had been burned at moderate to moderately-high severities. The predominant surface cover for each of these sites were pine needles and fine particles of charcoal. The final two sites (6, 9) were located near the deposition of the flow in areas that had been burned at moderate to moderately-high severities. The surface cover was predominantly pine needles at both of these sites. At each site we had to clear away the pine needles on the surface so that the mini-disk infiltrometer could properly
connect with the ground to form a suction. We cleared the pine needles by blowing them away as to ensure the least disturbance of the ground beneath the needles.

From the field data that we collected, we were then able to calculate infiltration rates. To do so, we used the USDA Rosetta software to obtain hydraulic parameters needed to estimate the flow rates from our mini-disk infiltrometer measurements (U.S.D.A., 1999). Rosetta uses pedo-transfer functions to estimate hydraulic parameters based on the USDA soil textural classifications. Additionally, due to the inherent uncertainty of the first measurement point of the data set, it is omitted. We ran the Rosetta software for our measurements for both sandy loam and loamy sand texture of soils.

**Rainfall Analysis**

In order to quantify the rainfall event that triggered the MDF, I obtained the rainfall rate data from three different gauge locations (Fig. 1). Two of these sites were Snow Telemetry (SNOTEL) gauges for the Natural Resources Conservation Service. The data for these SNOTEL sites could be downloaded from their website and they recorded inch per hour accumulated precipitation data. The gauges are a fluid-based system that use pressure transducers to convert the weight of new precipitation into volts, which is then converted by the system into inches of water. From the raw data I calculated hourly rainfall rates from September 2017 through September 2018. Because the gauges are fluid based sensors however, the data are susceptible to diurnal air temperature fluctuations and barometric pressure changes. I chose to use rainfall data from the Bear Grass and Smith Ridge sites because of their proximity to the study area and because their data fluctuated less than other nearby sites (NRCS, 2018a; NRCS, 2018b). The Bear
Grass gauge is 10 kilometers west of the study site and the Smith Ridge gauge is 8 kilometers west of the Study site (Fig. 1).

The third rainfall gauge is in the HJ Andrews Experimental Forest, which is located 40 kilometers west of the study site (Daley, 2018). The data are from a primary meteorological station within the forest, which records accumulated rainfall at 5-minute intervals. I downloaded this data from the Andrews Forest Long Term Ecological Research webpage. To compare this data to the SNOTEL sites I converted the 5-min rainfall intensities into hourly intensities. I also calculated peak rainfall intensities for the storm event for 5-minute, 15-minute, 30-minute, and 60-minute intervals using the HJ Andrews rain gauge data.

RESULTS

Debris Flow Path Characteristics

*Topography and Soils*

Despite the broad conical shape of Black Crater, there exist two main networks of channels on the northwest flank of the mountain that are incised on the order of meters (Fig. 2). These channels converge downslope, which determined the path of the debris flow. Analysis of the channel networks reveal that they terminate at Highway 242 located at the toe of the slope. The flank of volcano where the MDF occurred is mantled with soil that is continuous and over a meter thick at its base. The soil becomes thinner near the summit where patches of exposed, in situ bedrock are visible along the upper reaches of the debris flow location.

The MDF began as broad sheet-wash and rilling across a 0.8 km stretch near the summit of Black Crater. As the flow continued downslope, it became concentrated into
the two incised channel networks, converging to a width of 5-meters at its most narrow point. The MDF began to deposit material 80 meters upslope of the highway. The depositional area stretched across the highway and into the basin below, where it was confined by the lava flow at the base of the slope.

The flank of Black Crater where the debris flow initiated is gradually sloping with an average slope between 11 to 20 degrees. Only six percent of the basin is steeper than 30 degrees (Fig. 3). This steep area is located in a slope break that is present about halfway along the debris flow path and it marks a transition between the debris flow’s rill and sheet wash source area and the deeper erosional features downslope. The deepest erosional features along the debris flow occur directly downslope of this slope break and at the toe of the entire slope directly above the depositional area (Fig. 6). The combination of the topographic convergence and slope break in the basin resulted in the convergence of sediments that had been entrained across the wide hillslope. These topographic features contributed to the flow’s evolution from rills and shallow channels into deeper eroded gullies, entraining sediment and forming the subsequent debris flow.

**Debris Flow Features**

The MDF source area is characteristic of runoff-initiated debris flows observed in the literature. The source area is composed of a series of rills that are widespread across the slope. The rills range from 1-4 cm deep and some are discontinuous while others channel into deeper erosional features (Fig. 6). We also observed evidence of sheet wash in the source area, which appeared to remove the top few centimeters of material from the hillslope. The sheet wash exposed shallow root networks but did not appear to erode deeper than these structures.
From the source area, material converged into the incised channel networks, along which the erosional features deepened (Fig. 6). Within the center of the channels, the erosional features were deepest and eroded into the hillslope as uniform steps (Fig. 7). The erosional channels exposed roots and boulders and averaged to be between 10 to 20 cm deep. At the deepest points along the debris flow, the channels were incised to a meter depth. Additionally, splash lines from the debris flow were present on logs that had fallen perpendicular to the channel, revealing that during the event, flow depths exceeded 1.5 meters. Along the perimeter of the flow, shallower and wider channels were present and lined with coarse levees between 1 to 4 cm tall that were composed of pine needles, charcoal, and fine sediments.

The flow swept across Highway 242 in two locations from each channel network (Fig. 7). The flow deposited sediments below the toe of the hillslope, where the incised channel networks and topographic constraints stopped. The debris flow deposited sediment across Highway 242 and into the shallow basin on the northwestern side above the constraining Belknap Crater lava flows. The deposition was deepest in the center and thinned greatly toward the edges. At its deepest, the deposit was 1.62 meters deep. In total, $1.2 \times 10^4$ cubic meters of material was deposited by the debris flow’s two channel networks. The deposition was composed of fine to very fine grained, well sorted, poorly rounded, dark grey sediment and was extremely uniform.
Figure 6. Shows cross section of erosional depths along the hillslope. The cross section follows two paths: one from A to E along the north channel network and one from A to E along the southern channel network. Erosional depths are a compilation of data from both channel networks. (A) marks the upper limit of the source area, (B) marks the transition between source area and erosional features, (C) marks toe of slope where erosional features are deepest, (D) marks transition between erosional and depositional zones, and (E) marks the end of the depositional area. Vertical exaggeration of 5x.
**Fire Severity**

The entirety of the MDF occurred in the fire scar of the Milli Fire (Fig. 3). The source area of the MDF aligns with the patches of the forest that were burned at a high severity. Within the perimeter of the debris flow, all areas that had been burned at a high severity were observed to be source areas of the flow. Additionally, 52% of the MDF source area occurred within the high severity burn area, while the rest occurred directly downslope of these regions, suggesting that overland flow began in areas that were most severely burned. This displays a relationship between the initiation of this debris flow and the areas burned at high fire severity.

**Soil Infiltration Rates**

Field measurements of soil infiltration rates within the study area have a geometric mean of 24.9 mm h⁻¹ for loamy sand and 24.64 mm h⁻¹ for sandy loam. The data fits a lognormal distribution and has a standard deviation of SD= 30.6 mm h⁻¹ and SD= 29.96 mm h⁻¹ for loamy sand and sandy loam soil textures respectively (Fig. 8). The distribution of soil infiltration rates for loamy sand has a median of 33.6 mm h⁻¹ and an interquartile range of 17.9 mm h⁻¹ to 52.0 mm h⁻¹. The distribution of soil infiltration rates for the sandy loam soil texture has a median of 33.3 mm h⁻¹ and an interquartile range of 17.5 mm h⁻¹ to 50.9 mm h⁻¹. There is wide variability in infiltration rates across the study site.

Infiltrometer Sites 1, 2, 3, and 5 are located in the source area of the debris flow (Fig. 3). At these sites, fire severity ranged between moderately-high to high severities and the slope averaged between 21-30 degrees. The infiltration rates at these sites have a geometric mean of 28.5 mm h⁻¹ for loamy sand and 34.3 mm h⁻¹ for sandy loam.
Figure 7. (A) Photo of rills observed in the source area. (B) Photo of levee on perimeter of flow composed of pine needles, charcoal, and fine sediments. (C) Photo of erosional steps found along hillslope in the erosional area. (D) Photo of deep channel (>1-meter depth) observed in the narrowest section of the flow. (E) Photo of deeper channel in erosional area. (F) Photo of wider, shallower channel observed in transition zone between erosional and depositional areas. (G) Photo taken on June 20th, 2018 after the debris flow. Shows the deposition washed across Highway 242. (H) Photo of deposition upslope of Highway 242. Face of deposition visible due to bulldozer activity during highway clearing.
Additionally, the interquartile range for the sites in the source area is between 20.5 mmh⁻¹ and 36.6 mmh⁻¹ for loamy sand and is between 20.0 mmh⁻¹ and 59.5 mmh⁻¹ for sandy loam (Fig. 8).

Infiltrometer sites 4, 7, and 8 are located in the erosional section of the debris flow (Fig. 3). At these sites, fire severity ranged between moderate to moderately-high severities and slope averaged between 11-20 degrees. Infiltration rates at these sites have a geometric mean of 17.2 mmh⁻¹ for loamy sand and 15.48 mmh⁻¹ for sandy loam. Additionally, the interquartile range for the sites in the source area is between 3.0 mmh⁻¹ and 52.0 mmh⁻¹ for loamy sand and is between 6.4 mmh⁻¹ and 46.4 mmh⁻¹ for sandy loam (Fig. 8).

Lastly, infiltrometer sites 6 and 9 are located in the depositional area of the debris flow (Fig. 3). At these sites, fire severity ranged between moderate to moderately-high severities and slope averaged between 0-10 degrees. Infiltration rates at these sites have a geometric mean of 37.2 mmh⁻¹ for loamy sand and 34.7 mmh⁻¹ for sandy loam. Additionally, the interquartile range for the sites in the source area is between 21.1 mmh⁻¹ and 73.8 mmh⁻¹ for loamy sand and is between 22.0 mmh⁻¹ and 69.6 mmh⁻¹ for sandy loam (Fig. 8).

These differences between infiltration rates at different locations on the hillslope show spatial variability along the route of the debris flow. Such spatial variability is influenced by fire severity, slope, soil moisture, and other soil characteristics. The distributions reveal that there was less variability in the infiltration rates measured in the source area due to their smaller interquartile ranges. Additionally, it shows that there was
Figure 8. (A) shows distribution of infiltration rates for loamy sand and (B) shows distribution of infiltration rates for sandy loam. (C) shows boxplot distributions of all infiltrometer sites for loamy sand and sandy loam. (D) shows spatial boxplot distributions of loamy sand infiltration rates at source area, erosional area, and depositional. (E) shows spatial boxplot distributions of sandy loam infiltration rates at source area, erosional area, and depositional.
wide variability of infiltration rates in the erosional area, but within this, the data had a central tendency towards infiltration rates below 20 mm\(^{-1}\).

**Rainfall Analysis**

From the rainfall data collected at the HJ Andrews Experimental Forest, Smith Ridge SNOTEL, and Bear Grass SNOTEL gauges, I calculated rainfall rates for the storm event that triggered the debris flow and for storm events from the previous year. The rainfall rates that triggered the MDF on June 20\(^{st}\), 2018 were unusually high compared to rainfall rates from previous storms in the 2017 to 2018 year between when the Milli Fire and the debris flow occurred (Fig. 9). Additionally, the gauges revealed that during the June 20\(^{st}\) storm event, there were two distinct bursts of rainfall in which sustained, high-intensity rainfall occurred (Fig. 10).

The mean rainfall rates for the 2017 to 2018 year was 3.0 mm\(^{-1}\). Peak hourly rainfall rates for the storm event on June 20\(^{st}\) were 9.1 mm\(^{-1}\), 27.9 mm\(^{-1}\), and 27.9 mm\(^{-1}\) for the HJ Andrews, Bear Grass, and Smith Ridge rain gauges respectively. The HJ Andrews rain gauge reported that the first burst of rain during the June 20\(^{st}\) storm fell at a rate of 11.2 mm\(^{-1}\) for 15 minutes at 2:25pm. This was followed by the second burst, which fell at a rate of 25.4 mm\(^{-1}\) for a 15-minute duration at 4:05pm (Fig. 10). Over the course of the storm, 2.8 mm of rain fell during the first burst and 9.4 mm of rain fell during the second burst at HJ Andrews, resulting in a total of 12.2 mm of rainfall at the gauge over the course of the storm. Figure 11 reveals that high-intensity rainfall was sustained for 15-minute intervals at rainfall rates of 25.4 mm\(^{-1}\), 21.3 mm\(^{-1}\), and 17.3 mm\(^{-1}\) at the HJ Andrews rain gauge. This demonstrates that high-intensity rainfall was sustained for durations that could have been long enough to result in overland flow.
Figure 9. Graphs show rainfall intensities between 09/01/2017 to 09/01/2018, which is the year between the occurrence of the Milli Fire and the debris flow. (A) is rainfall at Bear Grass SNOTEL Site, (B) is rainfall at Smith Ridge SNOTEL Site, and (C) is rainfall at HJ Andrews Experimental Forest Site.
Figure 10. Graphs show hourly rainfall rates for the three rain gauges during the June 20th, 2018 storm event. (A) shows rainfall rates at Bear Grass SNOTEL site, (B) shows rainfall rates at Smith Ridge SNOTEL site, and (C) shows rainfall rates at HJ Andrews Experimental Forest site. The time count begins at 12:00 AM on June 20th, 2018.
Figure 11. Graph shows intensity-duration data for the rainfall rates recorded at HJ Andrews site during the June 20th storm event. The red ellipse is around peak 15-minute and 30-minute rainfall rates, all of which exceeded 15 mm h⁻¹ for the designated time interval. Shows that high-intensity rainfall was sustained for 15 to 30 minute intervals at this site.
Comparing these rainfall rates during the June 20th storm event to the soil infiltration rates, we find that there are locations on the hillslope where peak rainfall rates exceeded infiltration rates. Additionally, the geometric means for both soil textures’ infiltration rates are on the same order of magnitude as the peak rainfall intensities during the storm event. The peak rainfall intensities during the storm event that lasted for a duration of 15-minutes were 25.4 mm$h^{-1}$ and 21.3 mm$h^{-1}$, which could have resulted in overland flow at Black Crater. The peak rainfall intensity that lasted for a duration of 30-minutes was 16.3 mm$h^{-1}$, which could have resulted in overland flow at some locations on the hillslope.

**DISCUSSION**

My results suggest that the combination of high-severity fire and high-intensity rainfall at Black Crater resulted in the MDF, which was initiated by excess overland flow. The MDF followed patterns observed in the literature regarding fire severity, source area erosion, soil characteristics, and rainfall event. In addition, the conical and divergent topography of Black Crater is unique compared to basins in the literature where other runoff-initiated debris flows have been observed.

Studies on post-fire debris flows suggest that particular conditions pertaining to burn severity, topography, soil characteristics, and storm event all contribute to the susceptibility of a basin to produce a debris flow initiated by runoff (Meyer and Wells, 1997; Cannon et al, 2001; Wondzell and King, 2003; Cannon and Gartner, 2005; Parise and Cannon, 2012). The area of a hillslope burned at moderate to high severities is one of the most influential factors in whether or not a debris flow is initiated (Cannon et al, 2004; Cannon and Gartner, 2005; Gould et al., 2016). Of the 197 runoff-initiated debris flows studied by Gartner (in press), 91% of debris flows were initiated from basins with
more than 65% of their areas burned at moderate to high severities (Cannon and Gartner, 2005). At the MDF study site, 63% of the area was burned at moderately-high to high severities. What is especially notable, is that 100% of the source area for the MDF was burned at moderately-high to high severities (Fig. 3). Within this area, 52% was burned at high severities. This suggests that overland flow was initiated on the hillslope in areas where the soil was most influenced by fire and therefore where soil infiltration capacity was most reduced.

The Milli Fire that burned Black Crater in 2017 is noted to be the highest severity fire of the 2017 Oregon fire season (U.S. Forest Service, 2017). This fire fits into a broader trend of increasing frequency of high severity fires in the Pacific Northwest due to climate change (Gould et al., 2016). As high severity fires increase in frequency in the Pacific Northwest, this region could begin to experience more frequent runoff-initiated post-fire debris flows in the future. This pattern has been observed in interior British Columbia (BC), Canada where debris flows initiated via shallow-landsliding was the primary post-fire response in the region due to high soil infiltration rates and low rainfall intensities (Jordan and Covert, 2009). After the 2003 fire season, which was recognized as the most severe on record in BC, post-fire debris flows initiated via runoff were observed in multiple locations in the region (Jordan and Covert, 2009). Since the 2003 fire season, post-fire runoff-initiated debris flows have continued to be observed in interior BC (Jordan, 2016).

High fire severities are also responsible for producing fine sediments and ash on the soil surface, which are critical in the generation of debris flows (Meyer and Wells, 1997; Cannon et al, 2001). We observed fine-grained materials and fine-grained ash at
the MDF site. In addition, the depositional matrix was composed predominantly of fine to very fine-grained sediments. In some locations on the hillslope we observed fine-grained soils of a reddish-orange color, which is an indicator for high burn severity (Wondzell and King, 2003). This fine sediment is more susceptible to entrainment by overland flow than coarser, pre-fire sediment (Scott, 1971; Parrett, 1987). The high fire severity of the 2017 Milli Fire resulted in significant changes to soil characteristics and resulted in the production of finer sediments and reduced infiltration rates.

While excess overland flow does not typically occur in the Pacific Northwest due to the prevalence of low-intensity rainfall and notably high infiltration rates, the infiltration rates observed at the study site were significantly smaller than previously documented infiltration rates in the Pacific Northwest. In previous studies conducted in the Western Oregon Cascades, infiltration rates were found to range between 80.0 mm h⁻¹ to over 200 mm h⁻¹ (US Forest Service, 1973; Johnson and Beschta, 1980; Johnson and Beschta, 1981). In contrast, at Black Crater the observed infiltration rates had an average of 39.0 mm h⁻¹ and a geometric mean of 24.6 mm h⁻¹. Within the soil infiltration rate data collected at the study site, there is wide variation with a standard deviation between 29.9 to 30.6 mm h⁻¹. In addition, there is spatial variability between infiltration rates collected at different points of the flow. This could indicate differences in fire severity, soil moisture, or hydrophobicity at these locations on the hillslope. It is possible that the observed hydrophobicity exists in localized patches across the hillslope as has been observed at other study sites in the Pacific Northwest (Jackson and Roering, 2009).

In addition, the infiltration rates collected at the study site were most likely on the high end of rates to exist at the site for numerous reasons. First, the infiltration data was
collected from soil surfaces in areas adjacent to the flow that did not initiate the debris flow or become incorporated into the flow. This could indicate that the surfaces where the flow initiated or eroded had lower infiltration rates than the surfaces from which we collected the data. Additionally, the soil infiltration rate measurements were taken after the storm event that triggered the debris flow, which means soil moisture content was likely higher during our measurements than before the storm event. Therefore, it is possible the effects of hydrophobicity were reduced when our measurements were taken.

The 2017 Milli Fire was documented as having one of the highest soil burn severities of the Oregon fires during the 2017 fire season. Reduced infiltration rates observed at the study site can be attributed to the high burn severities during the Milli Fire. Had the rainfall rates that occurred during the June 20th storm event fallen on soil with infiltration rates characteristic of further west forests, excess overland flow would not have occurred. Rather, the combination of reduced infiltration rates and high rainfall intensities resulted in the occurrence of overland flow at the study site.

The storm event that triggered the MDF on June 20th had abnormally high rainfall rates for the 2017-2018 year (Fig. 9). The June 20th storm event had peak 15-minute rainfall rates of 25.4 mmh⁻¹ and 21.3 mmh⁻¹. The magnitude of this storm event has a return interval of two to five years (Oregon Department of Transportation, 2014). The June 20th storm event was also the first large storm of the summer, which means that this intense rainfall would have fallen on dry soil when hydrophobicity is at its most effective.

The rainfall rates during the storm event were on the same order of magnitude as the infiltration rates observed at Black Crater. Peak rainfall rates that lasted 15-minute durations exceeded the geometric mean of the soil infiltration rates. Due to the variability
within the infiltration rates observed at the site, there are patches of reduced infiltration where peak 30-minute intensities of 16.2 mm/h and 15.7 mm/h could have resulted in excess overland flow. Additionally, towards the summit the soil becomes patchier and thinner and in situ bedrock is visible. In these places where soil is thin or nonexistent, infiltration is negligible. Therefore, it is possible that at these locations where impermeable surfaces are present within the source area of the MDF, overland flow was further enabled.

There is uncertainty in the rainfall data because the rain gauge locations range from 10 to 40 kilometers away from the study site. As a result, we do not know the specific rainfall rates that occurred at Black Crater during the storm event. However, the rainfall rates from the three nearby rain gauges were on the same order of magnitude as the infiltration rates and the occurrence of excess overland flow is supported by field observations and the occurrence of a debris flow.

Overland flow leads to the entrainment of fine sediments in rills, sheet wash, and incised channels, which is essential in the bulking process that leads to the formation of debris flows (Scott, 1971; Parett, 1987). Topographic convergence is recognized as playing an integral role in this transition between overland flow and entrainment into a debris flow (Meyer and Wells, 1997; Cannon et al, 2001). The channel incision on the northwest flank of Black Crater is on the order of meters, which is much smaller than in basins observed in the literature that also produced debris flows (Swanson, 1981; Cannon et al, 2001; Gartner et al, in press). The lack of obvious topographic convergence on the seemingly divergent flank of Black Crater, sets the MDF apart from other runoff-initiated debris flows in the literature. While channel networks exist on Black Crater, they are on
the order of meters and not as defined as others observed in the literature, which make it surprising that this topographic convergence was capable of consolidating the 0.8 km-wide source area into the two defined channel networks.

Along the flank of Black Crater where the debris flow occurred, there is a slope break with a steepness, in sections, of over 40 degrees. This slope break is positioned at the transition point between the source area and the erosional area of the MDF, which could indicate that it played a role in the progression from rills to a debris flow. The slope break coincides with the head of the channel networks analyzed on the hillslope and the erosional features deepened from averaging 5 to 10 cm above the slope break to 15 to 20 cm deep at the toe of the break. Convergence on the hillslope becomes more prominent near the toe of the slope and the channel becomes more incised, which is where the MDF is at its narrowest point with a width of 5 meters. At this point on the hillslope, the channels become more incised and the depth of erosional features are between 50 cm to over a meter deep (Fig. 6). The slope break in combination with the convergence on this landscape contributed to the generation of a debris flow from surface runoff.

While the MDF is unique due to its location in the Pacific Northwest and its response to the divergent topography of Black Crater, it followed patterns observed in the literature regarding hillslope susceptibility to debris flow. The perimeter and source are of the MDF align with the USGS analysis of post-fire debris flow susceptibility in the Black Crater basin for rain falling at a rate of 24mmh⁻¹ for 15-minutes (Fig. 4). The model constructed by USGS considers all of the variables examined in this characterization of the MDF, which include fire severity, slope, soil texture, and topographic convergence (Staley et al., 2017). This could indicate that post-fire geomorphic response in the Pacific
Northwest could respond to conditions of fire severity and slope similarly to runoff-initiated debris flows observed in other locations.

CONCLUSION

This paper offers an in-depth characterization of the first documented post-fire runoff-initiated debris flow in the Pacific Northwest. There is extensive evidence that excess overland flow resulted in a debris flow on the flanks of Black Crater on June 20th, 2018. The combination of high severity fire, reduced infiltration rates, and a 2 to 5-year interval storm event resulted in the occurrence of the MDF.

My findings reveal that high fire severities resulted in dramatically reduced infiltration rates at the study site, which are significantly lower than other infiltration rates observed in the region. Rainfall rates during the June 20th storm event were on the same order of magnitude as the infiltration rates observed at the site, further supporting that excess overland flow occurred at this location. Despite the broad, conical shape of Black Crater, convergence and steep slopes on the hillslope promoted the transition between source area rilling and sheetwash to a fully mobilized debris flow. The location of the MDF aligns with the USGS analysis of post-fire debris flow susceptibility on Black Crater, which suggests that the MDF followed similar patterns that have been observed at other runoff-initiated debris flow study sites.

As fire seasons lengthen and fire intensity increases across the Pacific Northwest as a result of climate change, this region may become more susceptible to runoff-initiated debris flows. This characterization of the MDF can shed light on how runoff-initiated debris flows operate in the Pacific Northwest, which can contribute to our understanding of the factors that result in runoff-initiated debris flows in this region. It is essential that
future studies look into the susceptibility of the Pacific Northwest to runoff-initiated debris flows to better advise land management and safety decisions.
ACKNOWLEDGEMENTS

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I am also very grateful for my Carleton Advisor, professor Mary Savina. Thank you, Mary, for all of your feedback and support on this project and for always keeping your office door open to questions throughout the term! I would also like to thank all of my fellow geology majors for the fun and support over the last few years. Lastly, I am so grateful for my family and my friends—I couldn’t have done it without you!
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### APPENDIX.

#### Table 1. Black Crater Soil Infiltration Rates and Site Characteristics

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<th>Site</th>
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<th>Sandy Loam</th>
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