Wildfires in the West: Characterizing Drivers of Post-Disturbance Hydrologic and Sediment Response through Laboratory Analysis

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Abstract

Wildfires are a perennial problem across the western U.S. and internationally. By increasing watershed sedimentation rates to 25 times or more above non-wildfire base levels and raising concentrations of dissolved organic matter (DOM), fires create a major challenge for downstream water treatment plants. The overarching goal of this research effort is to test the response of sediment and runoff responses of soils at a range of burn severities, rainfall intensities, and terrain slopes. This paper will focus on the first phase of the project, exploring issues related to building the laboratory rainfall and wildfire simulators, and will discuss issues related to up-scaling of results to representative watershed scales to improve predictions of post-fire suspended sediment in streams.

Here we explore best practices for capturing burn, rainfall, and terrain related processes in the laboratory. The key experimental settings—burn temperature and duration, rainfall nozzle type and intensity—were determined based on published precedents and local historical observational data. Temperatures between 150 and 550°C, 30-minute burn duration, a FullJet® nozzle, and a maximum rainfall intensity of 2.5 in/hr were selected. We present synthetic results using a numerical model in order to anticipate how the soils will respond to the above settings to inform the subsequent laboratory testing. We have collected a series of soil samples from a steep mountain catchment with wildfire history: The Cache la Poudre (CLP) Basin near Fort Collins, CO that will form the basis of the laboratory experimentation. Samples will be exposed to burning and rainfall processes under combinations of burn temperature, rainfall intensity, and terrain slope, with differences in runoff sedimentation and DOM exports analyzed across these dimensions. A longer-term goal will be to apply up-scaling techniques of post-fire sedimentation prediction to entire catchments, in an effort to reduce uncertainty relative to either exclusively observational or model driven efforts to date.

1 Introduction

1.1 Post-Wildfire Sedimentation

Wildfires impact water supply and quality primarily by producing a large amount of ash and particulate, as well as increasing the hydrophobicity of soil (Scott & Van Wyk, 1990). This
combination results in increased runoff containing elevated levels of sediment in affected areas. The sediment in post-wildfire runoff poses a challenge for water treatment plants, not only because of the large volume, but also because of an increase in the concentration and reactivity of dissolved organic matter (DOM). DOM is the main substrate for the formation of carcinogenic disinfection byproducts during the water treatment process (Richardson et al., 2007). Therefore, there is a need for accurate predictions of sediment response due to wildfires to aid in treatment planning for these large influxes. Many studies have used observational data and simulation techniques (e.g. Kampf et al. 2016 and Larsen et al. 2009) to quantify the sedimentation response from soils after a wildfire event. However this study is unique in that it will enable a simultaneous evaluation of precipitation intensity, terrain slope, and burn severity on runoff and sediment response. This paper primarily describes construction of a laboratory scale rainfall and wildfire simulators to test sediment response under a range of precipitation intensities, terrain slopes, and burn severities. In addition, a discussion into up-scaling techniques using statistical and process-based approaches is included as a way to make much needed sediment response estimates at the catchment-scale.

According to Doerr et al. (2006) wildfires create a top layer of soil with low water repellency, consisting of combusted vegetation and charred soil, while increasing the water repellency of the soil directly beneath this layer. Post-fire rainfall events transport the loose sediment in the top layer and produce increased runoff, due to the increased water repellency of the lower layers of soil which allow less infiltration. This combination of effects causes a positive feedback in sedimentation rates in post-fire runoff (Benavides-Solorio & MacDonald, 2001).

Moody et al., (2009) report that a large number of field studies have attempted to quantify wildfire-sediment impacts across various regions and under different conditions, yet several key challenges exist with studying post-fire processes in the field. Most importantly, the highly variable conditions within any given catchment makes isolating the sedimentation responses solely from wildfires challenging. Moody et al. (2009) composed a meta-analysis of post-wildfire sedimentation across the western US and categorized basins on the basis of terrain slope and soil erodibility. A lack of correlation between sediment yield and these two factors suggested that other, less measurable factors, such as sediment supply, had a greater impact on the results. This finding underscores the challenges of developing a useful relationship between wildfire and sediment yield based on field measurements alone, in addition to the large time and costs associated with field analysis more broadly (Robichaud, 2005).

1.2 Context of this Study

This study is similar to other laboratory simulation studies that explore the effects of wildfire and rainfall intensity on runoff ratios, sedimentation, soil composition and water repellency, leachate, and other factors, with precise, quantitative results (Larsen et al. 2009, Cancelo-González et al. 2013, Keesstra et al. 2014, Kibet et al. 2014). However, few studies have taken a multivariate approach to the study of post-wildfire sedimentation response, studying multiple influencing factors and their interdependencies (e.g. Larsen et al. 2009). Our study is the first to incorporate specifically terrain slope, burn intensity, and rainfall intensity. When analyzing an area with consistent soil type and vegetation, these three variables cause the greatest amount of variability in sediment production (Yochum & Norman, 2015), suggesting that analyzing their variability simultaneously will offer key insights into the underlying processes and process interactions.

By using rainfall and burn simulation techniques in a controlled setting with laboratory-scale experiment, the impact on sedimentation from each variable—terrain slope, rainfall intensity, and burn intensity—in different combinations will give us a clearer understanding of how they affect sediment production towards the broader understanding of which characteristics make a
catchment most susceptible to increased sediment yield. The rest of this paper will detail the design processes and methods put into creating this comprehensive experiment, results, and future work.

2 Methods

2.1 Site Description

The study area is the CLP basin in the Arapahoe and Roosevelt National Forest near Fort Collins, CO. Draining 1915 mi² (4,960 km²) above the canyon mouth west of Fort Collins, this watershed produces approximately 274,000 ac-ft (338 x 10⁶ m³) of water per year (Coalition for the Poudre River Watershed, n.d.). It supplies most of the water for Fort Collins and other nearby cities: Greenley, Timnath, and Windsor.

The CLP Basin has a wide range of topographic relief, vegetation, and soil types. According to the USDA Cache la Poudre Rapid Assessment (2009), the vegetation in the mountainous area of the CLP is mostly categorized as forest and rangeland, containing a wide array of grasses and pine and spruce trees. The geology of the area is comprised mostly of several types of gneisses and granitic rocks, topped with rich topsoil promoting abundant vegetation growth. The river itself is 126 miles long, stretching from the Rocky Mountain range past Fort Collins where it turns into a meandering river, finally culminating near Greenly where it joins the South Platte River (Columbia Gazetteer, 2000). The CLP Basin is primarily under the jurisdiction of the National Forest Services, the National Parks Services, and privately owned land (USDA, 2009).

![Figure 1. The Cache la Poudre Basin overlain with the outline of the High Park fire.](image)

In 2012, a wildfire affected 85,000 acres (34,498 ha) of the CLP (USDA, 2017). The High Park Fire, started from a lightning strike on June 9, 2012 (City of Fort Collins, n.d.), destroyed 259 homes, displaced hundreds of residents, and resulted in one fatality before it was contained on July 1. Most of the CLP basin was burned at a moderate-high severity (Kampf et al., 2016). In addition to the damage done to homes and property, High Park had severe implications for the city’s water treatment plant. The large amounts of sediment produced by the wildfire inundated the water treatment plant, transported by the runoff from the basin. The plant responded by
increasing environmental monitoring, using multiple water supplies, and constructing a pre-sedimentation basin to continue delivering high-quality drinking water to its customers (Writer, 2014).

To simulate the effects of the High Park fire, soil samples for the laboratory experiments were taken from the CLP basin, near the edge of the burned area to obtain samples that are unburned, but have a similar soil composition. The samples were taken from a flat plot of land under tall, grassy vegetation. The soil was somewhat moist and black, rich with nutrients. There were very few rocks in the soil, making excavation less challenging. Sedimentation, chemical composition and runoff data collected in the CLP following the High Park Fire (Cotrufo et al. 2016, Kampf et al. 2016) will provide benchmark numbers to validate the results of this study.

2.2 Experimental Design

The major design elements in this study are of the rainfall and burn simulator structures, nozzle selection, burn method, sample tilting mechanism, and a subsequent runoff and infiltration collection system. The design of the rainfall simulator structure (Figure 2) was based on the protocol developed by Kibet et al. (2014), with a few alterations. A steel frame 91” tall was created, with a nozzle affixed to the top with a pressure meter, pressure gauge, flow meter and ball valve installed inline. The specifications of the simulator are more explicitly shown in the drawings in Figure 3.

Figure 2. Rainfall simulator created for a laboratory setting.
Droplet size and kinetic energy, rainfall intensity, and rainfall distribution were all considered when designing the rainfall simulator. Natural rainfall droplets range in size from 0.5 mm to 4 mm (Perlman, n.d.), which was emulated by choosing a nozzle type rated to produce a natural rainfall at a specific pressure: the FullJet® nozzles, the same type as used by Kibet et al. (2014). Each size can accurately produce only a short range of rainfall intensities, thus four sizes—HH-4.3W, HH-8W, HH-17WSQ, and HH-20W—were purchased to achieve the full range of desired intensities. Target rainfall intensity rates were determined by analyzing historical rainfall data from the area of interest, the CLP basin, using a National Oceanic and Atmospheric (NOAA) Precipitation-Duration-Frequency database (NOAA, 2005). The minimum and maximum intensity for the simulator were chosen as the 2-year and 100-year rainfall events, 0.76 – 2.5 in/hr (1.93 – 6.35 cm/hr), respectively. A series of tests were performed to determine the relationship between the pressure of the water in the system and rainfall intensity, confirming that the target intensities range are achievable by the rainfall simulator. Similarly, the distribution of the rainfall was tested to identify a configuration that produces a relatively uniform intensity spatial distribution.

A temperature-based burn severity scale was chosen, where moderate to severe wildfires range in temperature from 200°C to 400°C, respectively (Chander et al., 1983), and where mild fires rarely exceed 200°C (Jian et al. 2018). A wider range of temperatures, 150°C to 550°C, were chosen to fully encompass the soil property-altering effects of fire. A simulator with eight 375W heat lamps will be used to achieve this desired range of temperatures, similar to the heating method described in Cancelo-González et al. (2012). The surface vegetation and organic matter within the soil will combust in the process, creating ashy particulate as the basis of the sediment. The temperature distribution through the depth of the soil will be measured with thermocouples inserted into the side of each sample. The apparati will be attached to a cart so the simulation can occur safely outside.
Soil sampling has been done toward the goal of collecting undisturbed, whole soil samples to the extent possible for laboratory experimentation to be representative of natural conditions. Sturdy sample collection containers were created from 4 x 12” (10.16 x 30.48 cm) steel tubing with ¼” thick walls, cut into 4” (10.16 cm) segments (Figure 4a). This material was selected due to its resistance to high temperatures and rigid structure to hold the shape and structure of the samples. Holes drilled in the side of the samples allow for thermocouples to track the soil temperature in the burn simulation.

Lastly, once the soil samples have been collected and subject to burning and rainfall, collection of runoff and infiltration from soil samples in the simulator required creation of custom funnels (Figure 4b) which separately collect the infiltration and runoff water through separate outlets that are diverted to individual 10 oz. bottles. These collection funnels will be situated in a gridded tilting mechanism which will simulate various terrain slopes in the rainfall simulator. The contents of the bottles will be analyzed for sediment concentration and composition.

Figure 4. Soil sample in steel container (a) and custom funnel (b) created for collection rainfall infiltration and runoff from the soil samples, which are inserted inside, inserted in tilting mechanism.

2.3 Experimental Procedure

The first step in the simulation process is the selection of a location for soil sample collection. To ensure consistency in soil type, all samples were taken over a small footprint, a ¼ acre (0.101 ha) plot of land. Care was taken to obtain uniform and non-compromised soil structure following the method of the USDA NRCS South Dakota (2017). First, a rectangular outline slightly larger than the sample containers is dug into the plot of land with a spade, about 4” deep. Next, that rectangular piece of sod is gently lifted from the ground, trimming the vegetation roots connecting it to the ground, and placing the sample on top of a collection container. The edges of the sample are trimmed down with a hand saw to fit the form of the container, then pressed down gently until it is flush with the top and bottom of the sample container. This is repeated with enough samples to provide significant data points for the experiment.

Table 1 lists the experimental burn temperatures, precipitation intensities, and slopes. Samples are first placed in the burn simulator and burned to a certain temperature following the method used by Cancelo-González et al. (2012)—the heat applied just until the surface reaches the desired temperature, then turned off. Three thermocouples are placed into the sides of the samples at varying depths to track the temperature gradient throughout the soil.
Table 1. The range of experimental values for each variable.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Testing Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burn Temperature</td>
<td>100°C, 300°C, and 550°C</td>
</tr>
<tr>
<td>Precipitation Intensity</td>
<td>0.76 in/hr, 1.69 in/hr, and 2.50 in/hr</td>
</tr>
<tr>
<td>Terrain Slope</td>
<td>5°, 15°, 25°, 35°, and 45°</td>
</tr>
</tbody>
</table>

The burned and cooled samples are then placed in the rainfall simulator, to be run at varying rainfall intensities, with samples tilted at an angle reflective of terrain slope. The burned samples are tested in 1-hr runs in the rainfall simulator at all combinations of these variables. Testing of unburned samples provides an experimental control. Rain gauges placed in between the samples serve as references for the amount of rain applied to the samples, i.e. the rainfall intensity.

Runoff and infiltration waters flow into different sample bottles replaced at 10 minute intervals after samples are saturated, to capture the temporal change in sedimentation rates. Once the simulation is complete, the water-sediment solutions are run through a narrowly graded fiberglass filter to separate the sediment from water. Substrates are weighed to determine the ratio of sediment to liquid in the runoff and infiltration waters. The contents of the sediment are analyzed for the amount of dissolved organic material (DOM), total organic carbon (TOC), and grain size distribution through sieve analysis.

2.4 Synthetic Experiments

To complement the laboratory experiment, synthetic simulations of sediment rates and water fluxes in the samples were generated. Synthetic sediment data was generated via the Revised Universal Soil Loss Equation (RUSLE), chosen because it has the potential to incorporate the key dimensions of this study: burn-severity, slope, and rainfall intensity. RUSLE incorporates 6 soil and precipitation factors into its erosion estimate: the rainfall-runoff erosivity factor ($R$), the soil erodibility factor ($K$), the slope length factor ($L$), the slope steepness factor ($S$), the cover-management factor ($C$), and the support practice factor ($P$). These variables come together to form the following equation (Renard et al. 1997, Yochum et al. 2015):

$$ A = R \times K \times L \times S \times C \times P $$

Where $A$ is the estimated average soil loss in tons ac$^{-1}$ yr$^{-1}$.

Terrain slope is represented in the $L$ and $S$ variables, the equations for which are below:

$$ L = \left( \frac{\lambda}{22.13} \right)^m $$

$$ m = \left( \frac{\beta}{1+\beta} \right) $$

$$ \beta = \frac{\sin \theta}{0.0896 + 0.56} $$

$$ S = 3(\sin \theta)^{0.8} + 0.56 $$

Where $\lambda$ is the horizontal slope length (m), $m$ is the variable slope-length exponent, $\beta$ is the mean slope angle, and $\theta$ is the slope angle (degrees).

Rainfall intensity is represented in the $R$ variable, the equation for which is below:
\[ R = \sum EI_{30} \]  

(1e)

Where \( E \) is the energy for an individual storm (MJ ha\(^{-1}\)) and \( I_{30} \) is the maximum 30-minute rainfall intensity (mm hr\(^{-1}\)). \( R \) is the sum of the product of these two variables for every rainfall event in a year. For the purposes of our predictions, only the \( EI_{30} \) number for individual rainfall events is needed, which was calculated using an equation formulated by data collected in Wilson et al (2018):

\[ y = 4.3654x - 6.1333 \]  

(2)

Where \( y \) is \( EI_{30} \) (MJ ha\(^{-1}\) mm hr\(^{-1}\)) and \( x \) is total precipitation from a 30-minute storm event (mm). The rest of the variables in the RUSLE equation are constants determined by soil and vegetation properties. \( P \) is equal to 1 as no crop support practices are used in the majority of the CLP basin (Millward et al. 1999).

Though it was not originally intended for post-wildfire prediction, several studies have created alterations to the equation for this purpose. Yochum et al. (2015) used empirical data to derive multipliers for the soil erodibility factor, \( K \), which reflect the effect of mild, moderate, and severe wildfires on soil permeability: 1.5, 1.75, and 2.0, respectively. Similarly, Miller et al. (2003) calculated cover-management factors, \( C \), representative of the effects of mild, moderate, and severe fires on vegetation cover: 0.01, 0.05, and 0.2, respectively. These two studies used both of these modified RUSLE factors in their post-fire sedimentation calculations to represent the effect wildfires have on both soil erodability and vegetation cover. Therefore, using these equations and modified variables, RUSLE generated a synthetic sedimentation simulation following experimental values of terrain slope, rainfall intensity, and wildfire severity.

To generate synthetic runoff and infiltration rates in the soil samples, the modeling software HYDRUS 1D was used. Inputs reflecting actual experiment conditions were used to create the simulation: 4" (10.16 cm) soil samples comprised of sandy loam—a soil type common in the sampling area (Web Soil Survey, n.d.). A range of terrain slopes and rainfall intensities were then simulated using this setup. The effects of wildfires on the runoff and infiltration rates in the samples will be modelled by altering the hydraulic conductivity of the soil to reflect increased hydrophobicity, similar to the RUSLE simulations.

## 3 Results

### 3.1 Simulator Testing Results

The first project phase is complete—design and construction of the laboratory-scale rainfall simulator, but only partial construction of the burn simulator—so this section will focus primarily on the rainfall simulator testing. Intensity testing was performed to evaluate the simulator capability to consistently produce the minimum and maximum desired rainfall intensities, a 2-year and 100-year rainfall event: 0.76 – 2.5 in/hr (1.93 – 6.35 cm/hr), respectively. A total of 12 configurations were tested: the four nozzle sizes at three different system pressures, the pressure the nozzle is rated to plus 2 psi higher and 2 psi lower. The trials show that the higher and lower pressures can vary the rainfall intensity produced, but the rated pressure produces the least amount of variance in rainfall intensity through time (Figure 5).
Rainfall distribution tests to evaluate spatial uniformity in the rainfall were also completed using the same configurations and recording the distribution by taking measurements from 6 graduated cylinders placed in the bottom of the simulator. These tests showed that the smaller nozzles, rated to produce a lower rainfall intensity, have a much more evenly distributed rainfall intensity than the larger nozzles (Figure 6).

However, even the smaller nozzles produced a slight radial pattern in intensity distribution, indicating the importance of sample placement in the simulator to ensure desired intensities are reached. Overall, the nozzles had the most even distribution at their rated pressures, so these pressures were selected as the optimal operating pressures.
3.2 Synthetic Data Analyses

The RUSLE equation was applied to generate synthetic simulation data to provide insight into expected sedimentation response and for later comparison with laboratory scale results. With the altered $K$ and $C$ values to reflect the effects of wildfires (Yochum et al. 2013, Miller et al. 2003), sedimentation production was estimated for the same combinations of variables as will be done in the laboratory experiment. Figure 7 shows the RUSLE sedimentation rates for the variable combinations after a mild, moderate, and severe burn.

![Figure 7](image)

*Figure 7. Sedimentation estimations by RUSLE for a (left) low, (center) moderate, and (right) severe burn intensity. Note the different labels on the color bar, indicating much larger sediment responses with increasing burn severity.*

As expected, sedimentation varies monotonically in response to rainfall intensity, whereas it shows a sinusoidal relationship with slope angle. This is because the slope-dependent Equation 1c has the slope term in both the numerator and denominator. A key observation from these plots is that the largest increase in sedimentation relative to other factors results from increases in burn severity, due to increases in the $C$ and $K$ factors for each level of severity. This result is consistent with published findings (Benavides-Solorio et al. 2001) that report sedimentation increases more than 25 times.

To model the runoff and infiltration from the individual samples, a HYDRUS 1D model was implemented at a range of rainfall intensities and terrain slopes. Drainage from the bottom of the samples was modeled in addition to runoff and infiltration, since these targets for collection from the rainfall simulator (Figure 8). As expected, increasing the terrain slope produces increased runoff, and decreased drainage. The results show that at maximum rainfall intensity, runoff will start after 12 minutes and drainage after 24 minutes. These estimates will inform the design of the rainfall sampling protocols.
Figure 8. Simulated cumulative runoff (left) and cumulative drainage (right) from a single soil sample, produced from maximum rainfall intensity, 2.5 in/hr (6.35 cm/hr), where soil samples are at a range of terrain slopes.

4 Discussion

4.1 Future Work

The first phase of this project, the creation of a laboratory-scale rainfall simulator, has been completed, including a tilting mechanism to simulate varying terrain slopes and a system that collects and separates runoff and infiltration. Intensity and distribution test results show that the simulator is capable of emulating natural precipitation at the desired target intensity. The burn simulator structure and methods have been designed, and construction is underway. RUSLE results provided a synthetic simulation of the relationship between key variables and sediment response, and HYDRUS 1D provided predictions of runoff and infiltration. The next steps for this project are finishing the construction and testing of the rest of the equipment, then collecting additional soil samples, testing them in the burn and rainfall simulators, and finally analyzing the runoff and infiltration produced from the experiments.

Once sedimentation response has been analyzed across all variable combinations a broad goal is to up-scale these responses to entire basins. Each of these combinations of conditions can be associated with representative hillslopes within a given catchment to predict net sedimentation response. This concept was used by Yochum et al. (2015) to create a catchment-scale model of post-fire flood hazards. Notably, our study will use laboratory data instead of field data to inform the up-scaling.

This up-scaling analysis can be achieved in two different ways, using statistical analysis or applying a physically-based hydrologic model. A statistical model (regression, categorical, etc.) relating the three variables with sedimentation response can be up-scaled on the basis of the distribution of these three variables across a given catchment. Similarly, the parameters of an existing physically-based model (e.g. HSPF) of sedimentation response can be calibrated to the laboratory data and then applied to a given catchment.

Several studies exist forming a general relationship between the High Park Fire and its impact on the sedimentation in the CLP River, which will be compared to the net sedimentation prediction formed by the laboratory-scale experiment and subsequent up-scaling (Cotrufo et al. 2016, Kampf et al. 2016). In addition, the RUSLE analysis will be used to compare the sedimentation response due to each combination of the three variables to that observed in the
experimental analysis, determining whether the experimental data follows the same variable-dependent trends as RUSLE.

4.2 Uncertainty Analysis

Key sources of uncertainty in this analysis arise from the sampling process, as well as the instruments used to measure rainfall, the liquid/solute ratio in the runoff and infiltration, chemical composition and particle size distribution of the sediment. The largest source of uncertainty for the future analysis will come from assumptions needed to upscale the sediment response from the soil samples to the basin scale, as the length of hillslope in a sedimentation calculation greatly affects the results. Importantly, we expect that the sedimentation rate for an entire basin will be smaller than for a smaller segment of the basin, due to sediment trapping and deposition along the route to the catchment outlet (Le Bissonnais et al., 1998). To this end, an extra factor for length scaling will be implemented to account for up-scaling effects and sediment trapping.

5 Conclusion

The purpose of this study was to build a framework capable of addressing key knowledge gaps into the impacts of wildfires on sedimentation responses at catchment scales. This information will be valuable to water treatment planning efforts to anticipate the influx of sediment in water sources originating from catchments stricken by wildfire.

The post-wildfire sedimentation predictions from the models created in this experiment will be unique relative to extant research to date, most notably by simultaneously analyzing multiple sedimentation controls in a consistent framework. These results are expected to highlight the relationship between terrain slope, rainfall intensity, and burn severity and their effects on sediment production and chemical composition. In addition, the rainfall simulator and burn simulator will have the capacity to be used for future experiments, together or independently.
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