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Effects of post-wildfire erosion and wildfire ash on water quality

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ABSTRACT

The eroded sediment and ash from wildfire-burnt hillslopes can move into downstream waterbodies and deteriorate water quality, which can pose challenges to aquatic life and drinking water treatment plants. This study investigates the effects of ash on runoff and sediment loss and the impacts of eroded soil and ash on water quality for a site burned by the 2021 Green Ridge Wildfire, WA. Indoor rainfall simulation experiments were performed to simulate three wet-dry cycles on burnt soil (S-plots) and burnt soil overlaid by ash (A-plots). The runoff and sediment loss were measured during each wetting. The pH, electrical conductivity (EC), settled water turbidity (SWT), dissolved organic carbon (DOC), and total dissolved nitrogen (TDN) concentrations were also measured. The cumulative runoff was 18 L from S-plots and 16 L from A-plots, and the cumulative sediment loss was 1656 g from S-plots and 925 g from A-plots. The pH of the runoff from S-plots and A-plots was as high as 8.2 and 9.0, respectively. The DOC concentration was as high as 18 mg/L for S-plots and 10 mg/L for A-plots. The TDN concentration reached a maximum of 6 mg/L for S-plot and 2 mg/L for A-plots. The maximum SWT was 3225 NTU for S-plots and 3040 NTU for A-plots. The simulated post-wildfire erosion resulted in high pH, DOC, TDN, and SWT of the runoff that may negatively impact aquatic life and water treatment processes if mitigation measures are not implemented or streamwaters do not buffer or dilute the effects of the runoff.

Keywords: Wildfire, wildfire ash, post-wildfire erosion, water quality

1 INTRODUCTION

The frequency and severity of wildfires has been increasing in the United States (Hoover and Hansen 2021). Post-wildfire erosion is common and is a concern with respect to the safety of the increasing population in or near wildfire-prone regions where destructive floods can cause catastrophic damages, loss of life, and deterioration of water quality (Pausas et al. 2008; Hohner et al. 2019) The burning of protective canopy and roots as well as the changes in ground conditions such as formation of water repellent layers in soil make hillslopes prone to erosion (Robichaud et al. 2016).

During a wildfire, the available fuel (e.g., vegetation, litter and duff, and soil organic matter) combusts and transforms into ash. The chemical and physical properties of wildfire ash can be highly variable, depending on the level of combustion of the available fuel (Roy et al. 2010, Bodi et al. 2011). Light gray to white, wettable ash is formed after complete combustion (Gabet and Sternberg 2008), whereas incomplete combustion produces dark gray to black, water repellent ash (Bodi et al. 2011). Wildfire ash affects the runoff and erosion (and consequently the surface water quality) and has important implications for post-fire management. Many studies suggest that ash seals the soil surface by clogging macropores and increases runoff (Etiegni and Campbell 1991; Onda et al. 2008), while other studies demonstrate that ash reduces runoff by storing water (Mallik et al. 1984; Gabet and Sternberg 2008). Ash has been reported to increase erosion by providing readily erodible sediment (Cannon et al. 2001; Shakesby and Doerr 2006). However, some studies showed that ash reduces erosion by protecting the soil from raindrop impacts (Leighton-Boyce et al. 2007; Woods and Balfour 2008). The uncertainty associated with the potential impacts of ash on runoff and erosion warrants further research.

The eroded soil and ash can deteriorate the surface water quality (e.g., Brito et al. 2021) and negatively impact the aquatic life (e.g., Smith and Caldwell 2001). Of the studies reviewed by Paul et al. (2022) on the impacts of wildfires on water quality, almost half reported an increase in pH, 69% reported an increase in EC, 91% reported an increase in turbidity, 48% reported an increase in organic carbon, and 77% reported an increase in nitrogen. The pH of water has a direct effect on aquatic life. Extreme pH can stress the aquatic animals and may also lead to deaths (Kasper et al. 2022). Additionally, pH can affect aquatic life indirectly as it impacts the mobilization and toxicity of pollutants (Bourg and Loch 1995). EC, the ability to conduct electric current, is related to the concentration of ions from dissolved salts and inorganic compounds (Miller et al. 1988). An increase in EC can stress the aquatic life, influence drinking water treatment, and impact particle stability in aquatic systems (Gregory 2005). Organic carbon and nitrogen play an important role in drinking water treatment as they control the formation of disinfection byproducts (DPBs) and metal binding (e.g., Regan et al. 2017). Furthermore, elevated nitrogen inputs in streamwaters can lead to harmful algal blooms which can potentially impact the food web and have negative effects on aquatic life (Chorus and Welker 2021). Turbidity is a measure of relative clarity of water and is related to the amount of suspended solids present. Post-wildfire increases in streamwater turbidity can challenge drinking water treatment and aquatic life (e.g., Hohner et al. 2016; Rust et al. 2019).

The post-wildfire effects on water quality may be due to the mobilization of burnt soil and ash to the nearby waterbodies, However, it is difficult to evaluate the specific impacts of ash on water quality due to differences in ash properties, changes in physicochemical properties of ash upon interaction with wind and water, and its redistribution (Smith et al. 2011; Bodi et al. 2014). In this study, indoor rainfall simulation experiments were performed to evaluate the erosion of soil and ash collected from an area burnt by the 2021 Green Ridge Fire in Washington State. The effects of ash on runoff and erosion due to three wet-dry cycles were investigated. The runoff samples were analyzed to evaluate the impacts of eroded soil and ash on pH, EC, DOC, TDN, and SWT.

2 STUDY SITE

Soil and ash samples were collected from Green Ridge Fire, located 30 miles east of Walla Walla, in the Pomeroy Ranger District of Umatilla National Forest, Washington. Lightening started a fire in the region on July 7, 2021, which was contained on October 4, 2021. Over the span of 3 months, the fire burned 18,300 ha. Burned Area Emergency Response (BAER) teams classified the soil burn severities as follows: 29% area as unburned or very low, 52% as low, 17.5% as moderate, and 1.5% as high according to the classification by Parsons et al. (2010). Approximately 21.8% slopes in the region are less than 15°, 58% are between 15° and 30°, 20% are between 30° and 45°, and less than 1% of the slopes are greater than 45°. Soil and ash samples were collected two weeks after the containment of the fire from a moderate soil burn severity area of approximately 30° slope. The dominant vegetation in the region includes ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), and lodgepole pine (*Pinus contorta*). The watershed within the burned perimeter contains two major water bodies- Meadow creek and Panjab Creek, which drain into the Tucannon River, a tributary of the Snake River. The Tucannon River flows through the burnt region for approximately 18 km.

3 MATERIALS AND METHODS

3.1 Soil and ash characterization

Particle size distribution of soil and ash was measured with Pario Automated Particle Size Analyzer (Meter Group, Pullman, WA). Soil contained 12.6% sand, 87.3% silt, and 0.1% clay, while ash contained 7.3% sand-sized, 92.6% silt-sized, and 0.1% clay-sized particles. The specific gravity of soil and ash solids was 2.66 and 2.52, respectively (ASTM D854-14). Water Droplet Penetration Time (WDPT) test was performed to evaluate the wettability of soil and ash as described in Akin and Akinleye (2021). Both soil and ash had WDPT < 1s and were classified as hydrophilic (Van't Woudt 1959).

3.2 Rainfall simulation experiments

The sampled soil was sieved, as described in Akin et al. (2021), through a custom-made sieve having an opening size of 0.63 cm to homogenize the soil and to remove large gravels, roots, and stems. Soil was compacted in metallic plots at the natural water content (2.75 ± 0.5%) and a target void ratio of 2.1 to simulate post-fire field conditions. The total thickness of the compacted soil layer was 9 cm. In addition to the plots containing only burnt soil (S-plots), ash covered plots (A-plots) were also prepared to assess the impacts of ash on erosion and water quality. In A-plots, 0.49 kg of ash was sprinkled on the soil surface as a loose, uniform, 1-cm thick layer. This was done to replicate field conditions where ash is naturally settled on the ground. The ash layer in A-plots had 96% porosity. Two replicates of both type of plots were used.
Rainfall was simulated on the plots following the methods by Akin et al. (2021). The plots were subjected to three wet-dry cycles. During wetting, the plots were inclined at 30° under the rainfall simulator. The 30° slope was selected as most of the hillslopes in the region (80%) are less than 30°. The plots were placed horizontally under two 5700 W ultraviolet light source for drying. For each wetting event, rainfall was applied at an intensity of 100 mm/h for 30 min to simulate a high-intensity storm. In the region containing the study site, a 15-min rainfall of 50 years return period has similar intensity (e.g., Demissie et al. 2016). After the first and the second wetting events, the plots were dried for 4 h and 8 h, respectively. The drying times were selected to simulate drying between successive rainfalls. The experiments were terminated after the third wetting event. After each wetting and drying event, samples were collected from the top 2 to 3 cm of the plots from three different locations and the surficial water content was measured.

During each wetting event, runoff samples from the plots were collected at 5 min intervals until no more runoff was generated. From each runoff sample, depending on the total volume, 1-, 2-, or 3-30 mL aliquot samples were separated and stored at 4 °C for water quality measurements. The remaining runoff was passed through Whatman 40 filter (2.5 μm pore size) using a Buchner funnel filtration setup. The sediment retained on the filter paper was oven-dried at 105 °C to obtain the sediment loss from the plots. The filtered runoff samples were stored at 4 °C until analysis.

3.3 Water quality measurements

The water samples from the runoff were hand-mixed thoroughly for 5 min using end-over-end method. After mixing, the samples were settled for 10 min. The pH and EC of the supernatant were measured using the VWR Symphony B10p probe (ASTM D4972-19) and Orion conductivity meter, respectively. All pH and EC measurements were taken at 25 °C.

DOC and TDN were measured using a Shimadzu TOC-V Analyzer with nitrogen module. The instrument measures DOC using the high-temperature combustion catalytic oxidation method. In this technique, samples are heated to elevated temperatures (680 °C) in an oxygen-rich environment in the presence of platinum catalyst and the amount of CO_2 generated due to the combustion of carbon is detected by nondispersive infrared sensors. TDN is measured using the catalytic thermal decomposition/chemiluminescence method in which nitrogen in a sample is oxidized and converted into nitrogen oxides which are detected by a chemiluminescence detector. The filtered runoff samples were again passed through Whatman GF/F filters (0.7 μm pore size) to remove the particulate organic carbon and nitrogen (APHA/AWWA). The pH of the samples was reduced to approximately 2 by adding 6 to 7 drops of 6N HCl. This was done to oxidize the inorganic carbon present in the samples prior to DOC measurements (e.g., Avramidis et al. 2015).

Turbidity of the aliquot samples was measured using a Hach TL2300 turbidimeter (ASTM D7315-12). Initially, the aliquot samples were mixed thoroughly and immediately placed inside the instrument for measurements. However, for some samples, the turbidity exceeded the highest measurable limit of the instruments (i.e., 4000 NTU). Therefore, the samples were allowed to sit for 60 min and the settled water turbidity was measured.

4 RESULTS

4.1 Runoff and sediment loss

The runoff and sediment loss measured at 5-min intervals were added to obtain cumulative runoff and cumulative sediment loss during each wetting event (Figure 1). The average surficial water content of the plots after each wetting and drying event are shown in Figure 2. Negligible runoff (< 100 mL) and sediment loss (< 2 g) was measured from both S-plots and A-plots during the first wetting event as the soil (in S-plots), and soil and ash (in A-plots) were becoming saturated. The surficial water content after the first wetting event was 42% in S-plots and 58% in A-plots. The first drying event reduced the water content in S-plots and A-plots to 38% and 34%, respectively.

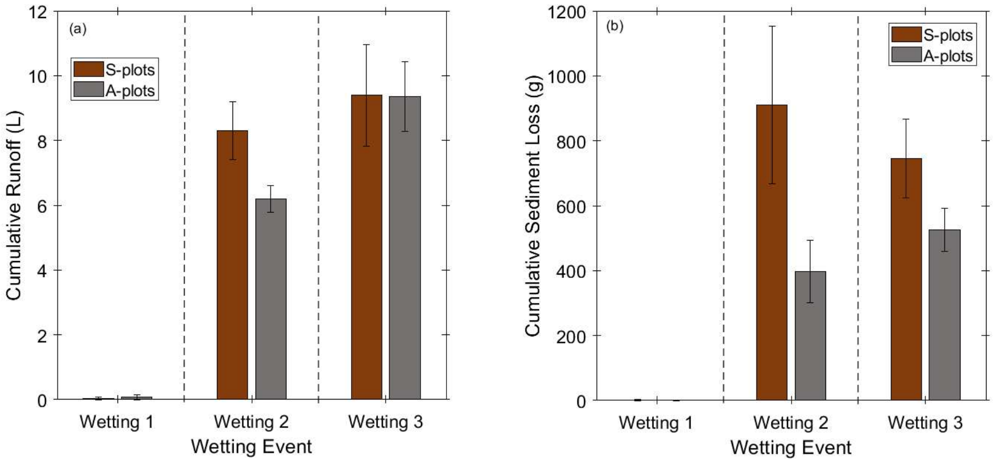

Figure 1: (a) Cumulative runoff, and (b) cumulative sediment loss from burnt soil plots (S-plots) and ash-covered plots (A-plots) during the three wetting events.

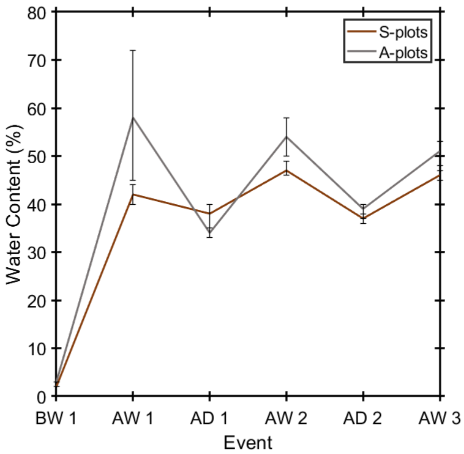

Figure 2: Surficial water content values of S-plots and A-plots before first wetting event (BW1), after first, second, and third wetting events (AW1, AW2, and AW3), and after first, second, and third drying events (AD1, AD2, and AD3).

In the second wetting event, runoff started after 5 min from S-plots and after 10 min from A-plots. Cumulative runoff from the S-plot was 8.3 ± 1.3 L and from A-plots was 6.2 ± 0.4 L (i.e., 25% lesser than S-plots). The sediment loss from S-plots was 910 ± 243 g and from A-plots was 398 ± 96 g (56% lesser than S-plots). The second wetting event increased the water content to 47% in S-plots and 54% in A-plots. After the second drying event, S-plots and A-plots had similar water contents (37% for S-plots and 39% for A-plots).

Runoff started after 5 min from both S-plots and A-plots in the third wetting event and similar cumulative runoffs were generated. The mean cumulative runoff was 9.4 ± 1.6 L (from S-plots) and 9.3 ± 1.1 L (from A-plots). The mean cumulative sediment loss from A-plots was 30% less than S-plots in third wetting. The water content of S-plots and A-plots after the third wetting event were 46% and 51%, respectively.

4.2 pH and Electrical Conductivity

The average pH of the runoff from S-plots in the first, second, and third wetting events were 8.2, 7.9, and 8.0, respectively (Figure 3a). The pH of the runoff from A-plots was greater than S-plots in first wetting (pH 9.0) and second wetting (pH 8.8). However, in the third wetting, the pH was same for both S-plots and A-plots (pH 8.0). The average EC of the runoff from S-plots was 456 µS/cm in first wetting, 524 µS/cm in second wetting, and 514 µS/cm in third wetting (Figure 3b). In all three wetting events, the EC of runoff from A-plots was greater than S-plots (1033 µS/cm in first wetting, 738 µS/cm in second wetting, and 692 µS/cm in third wetting), however, the difference reduced with each wetting. The EC values of the runoff from A-plots were high for the first 5 and 10-min intervals (1501 µS/cm and 1252 µS/cm, respectively) and decreased thereafter. This variation is represented by the error bars in Figure 3(b).

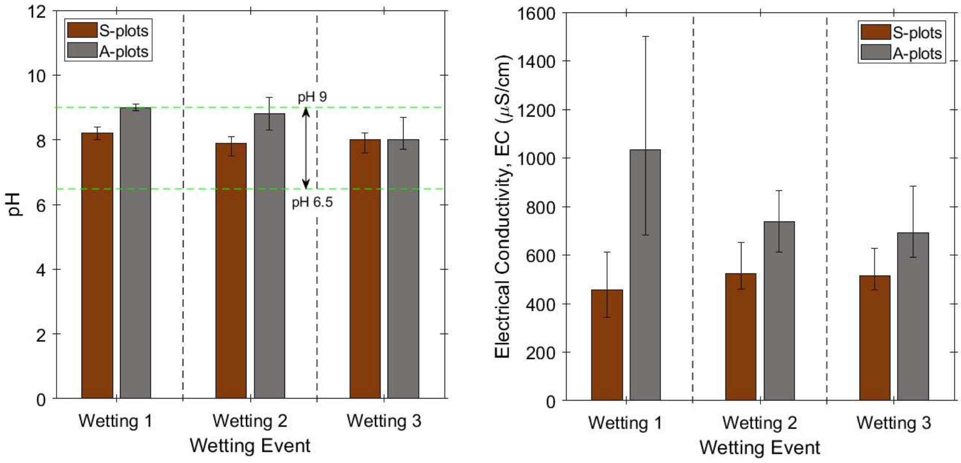

Figure 3: (a) pH, and (b) Electrical Conductivity of the runoff from S-plots and A-plots and the EPA's recommended surface water ranges of pH (US EPA 2000) for aquatic life (shown with dashed lines and arrows). Post-wildfire runoff will be diluted and buffered by the background water quality of streams and therefore the comparison to the EPA guidelines should be considered in this context.

4.3 Dissolved Organic Carbon and Total Dissolved Nitrogen

The runoff volume generated from both S-plots and A-plots in the first wetting event was insufficient for DOC and TDN measurements. Therefore, DOC and TDN was measured only for second and third wetting events. The average DOC concentration of the runoff from S-plots in second wetting was 14 mg/L and in third wetting was 18 mg/L (Figure 4a). The average DOC concentration from A-plots was 9 mg/L in second wetting (36% lower than S-plots) and 10 mg/L in third wetting (44% lower than S-plots). The average TDN concentration in the runoff from S-plots in second and third wetting was 6 and 3 mg/L, respectively, and from A-plots was 2 mg/L in both second and third wetting events (Figure 4b). The DOC and TDN concentrations were typically higher for the first 5 and 10-min intervals and relatively lower for the remaining intervals. The error bars in Figure 4 represent the variation in DOC and TDN concentrations with time for each wetting event.

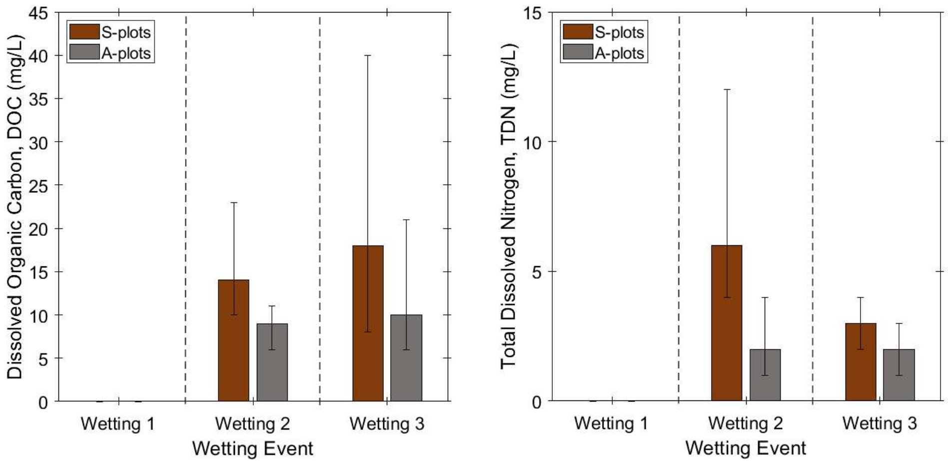

Figure 4: (a) Dissolved Organic Carbon, and (b) Total Dissolved Nitrogen in the runoff from S-plots and A-plots

4.4 Settled Water Turbidity

Average SWT of the runoff from S-plots was 42 NTU in first wetting, 3225 NTU in second wetting, and 2464 NTU in third wetting (Figure 5). For A-plots, SWT of the runoff was 209 NTU (first wetting), 807 NTU (second wetting), and 3040 NTU (third wetting).

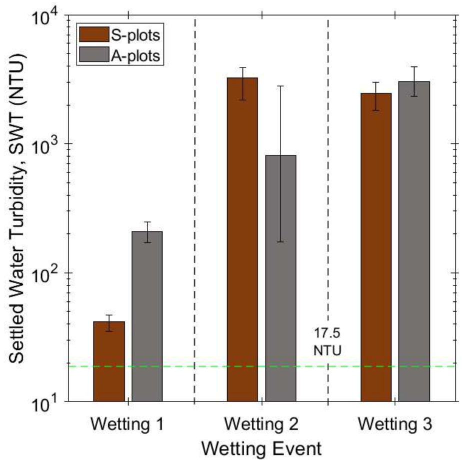

Figure 5: Settled water turbidity in the runoff from S-plots and A-plots. EPA's recommended criteria for turbidity in rivers and streams vary based on the Ecoregion (US EPA 2000); dashed lines show the recommended concentrations for turbidity in surface waters for Ecoregion 10, which have the maximum upper limits. The turbidity of the post-wildfire runoff will be diluted by the background water quality of streams and therefore the comparison to the EPA guidelines should be considered in this context.

5 DISCUSSION

5.1 Effects of ash on runoff and sediment loss

In the beginning, burnt soil provided a water storage capacity of 61.0 mm in both S-plots and A-plots. The ash layer provided an additional water storage capacity of 9.6 mm in A-plots thereby increasing the storage capacity to 70.6 mm. The entire rainfall in first wetting (i.e., 50 mm) only increased the saturation without producing any runoff, but the plots did not reach 100% saturation by the end of first wetting as the rainfall was less than the water storage capacity of the plots.

In the second wetting event, runoff had a delayed start because rainfall was still saturating the plots. The extra 5-min delay in runoff generation from A-plots was due to the additional water required for saturation of the ash layer. Similar observations were made by Woods and Balfour (2008) where a 1-cm thick layer of ash delayed the runoff by approximately 5 min under similar rainfall conditions. The lesser sediment loss from A-plots reflects the combined effect of lower runoff and reduced sediment detachment due to raindrop impacts. The ash layer reduces the rainsplash erosion and protects the underlying soil (e.g., Benavides-Solorio and MacDonald 2001; Cerda and Doerr 2008; Woods and Balfour 2008). At the end of the second wetting event, the water content in A-plots was 54%, which is lower than the water content after the first wetting event (58%). This observation suggest that the second wetting event resulted in movement of some amount of ash with the runoff and reduced the amount of ash available in A-plots. Still, ash acted as a protective layer and resulted in 56% less erosion than the S-plots.

At the end of the third wetting event, A-plots had 30% less sediment loss than S-plots. This was attributed to progressive loss of the ash layer with runoff, which also resulted in 32% more sediment loss in A-plot in the third wetting event compared to the second wetting event. Both A- and S-plots produced a similar amount of runoff, unlike the second wetting event. It is also possible that some amount of ash moved into the uppermost soil, clogged the pores, and sealed the surface during the second wetting event (e.g., Neary et al. 2005; Gabet and Sternberg 2008; Onda et al. 2008). A similar degree of surface sealing might have occurred in S-plots in the second wetting event due to raindrops destroying the soil aggregation, compacting the uppermost soil, and reducing the pore space (e.g., Valentin Bresson 1992; Woods and Balfour 2008). The sediment loss from S-plots reduced in the third wetting event by 18% compared to the second wetting event despite a 13% increase in runoff, which was attributed to the compaction of uppermost soil due to raindrop impact.

5.2 Effects of burnt soil and ash on water quality of runoff

Wildfire ash typically increases the pH of the runoff water by two to three units (e.g., Ulery et al. 1993). The higher pH values for A-plots in the first and second wetting events compared to S-plots suggest that some amount of ash was transported with the runoff. However, in the third wetting event, the proportion of ash in the transported sediment decreased due to reduced availability, resulting in pH value similar to the S-plots. The mean pH of the runoff from S-plots is within the streamwater pH 6.5-9 safe limit for aquatic life (US EPA 2000) for all the wetting events. Although, it is equal, or close to the upper limit of pH 9 for A-plots, the effects of the runoff on receiving surface waters will be diluted and buffered by the background water chemistry. Therefore, the erosion of ash may potentially increase the pH of downslope surface waters and create challenges for aquatic life depending on the volume of runoff and water quality characteristics of the stream. Wildfire ash can contain a variety of inorganic constituents such as calcium, magnesium, potassium, silicon, phosphorus, sodium, and sulfur (Qian et al. 2009; Gabet and Bookter 2011). Compounds of these elements dissociate in water and increase EC (Pereira et al. 2012). Higher EC means higher ionic strength and can increase particle interactions (Gregory 2005). The higher EC of runoff from the A-plots in first and second wetting events suggest that the ash particles may have greater interaction and lower particle stability than soil in aquatic systems, which means the downstream mobilization of ash would be less than soil. However, many other factors that govern particle stability such as porosity, size, and surface charge might have different impacts and must be considered to evaluate the overall particle stability and downstream transport.

The increased DOC in S-plots in third wetting could be due to higher runoff volume which likely dissolved and transported more carbon from the plots. The DOC concentrations from the A-plots were less than the S-plots in both the second and third wetting events, likely due to lower sediment loss in A-plots. The observations suggest that the presence of ash results in lower DOC concentration in runoff due to lesser sediment loss however, the contribution of wildfire ash to carbon concentration depends on the type of ash which, in turn, depends on the combustion completeness. For instance, Rodela et al. (2022) found that the water extractable organic carbon concentration was lower for white ash and black ash whereas, it was higher for gray and dark gray ash. EPA does not have recommended limits of DOC for aquatic life; however, it is a key parameter that controls the formation of toxic disinfection byproduct (DBP) and drinking water treatment process design (USEPA 2010). Hydrophilic wildfire ash typically contains little organic nitrogen (Almendros et al. 2003; Knicker 2011) which explains the lower TDN concentration from A-plots relative to S-plots. The TDN concentrations in the runoff water from the S-plots (6 mg/L in second wetting and 3 mg/L in third wetting) and A-plots (2 mg/L in second and third wetting) are greater than, or close to the EPA's recommended limits for TDN in rivers and streams for aquatic life [0.12 -

2.18 mg/L, depending on the ecoregion (US EPA 2000)]. This suggest that the transport of wildfire-burnt soil and ash into the downstream water bodies may cause challenges for aquatic life if there is not adequate dilution by the receiving water, or erosion mitigation measures are not in place. Furthermore, elevated nitrogen levels in source water supplies can lead to the formation of nitrogen based DBPs and cause challenges for drinking water treatment process (Liew 2016).

The decrease in turbidity in the runoff from the S-plots in third wetting event can be attributed to the combined effect of increased runoff and reduced sediment loss. The turbidity in the runoff from the A-plots increased by 277% in the third wetting event relative to the second wetting event, even though a 50% increase in runoff was observed in the third wetting event. The results suggest that the sediment moving with the runoff in the third wetting event was primarily burnt soil which made the runoff water more turbid.

6 CONCLUSIONS

The results from the rainfall simulation experiments suggest that hydrophilic ash provides additional water storage, delays runoff generation, reduces total runoff, and lowers sediment loss by protecting the underlying soil from rainsplash erosion. However, ash eventually moves along the slope and into the soil, and results in increased runoff and sediment loss. Both burnt soil and ash present in runoff may increase the pH in receiving waterbodies and can potentially have negative impacts on aquatic life, depending on the background pH and buffering capacity of streams. Similarly, both burnt soil and ash in runoff may increase EC however, the increase is greater for A-plots (plots containing ash). Higher EC from A-plots suggest lower particle stability in aquatic systems. However, several other parameters control the particle stability and must be considered.

The DOC concentration was higher in the runoff from S-plots due to the higher sediment loss. Ash reduced the sediment loss which resulted in lower DOC concentrations in the runoff from A-plots. The additional carbon load to surface waters due to post-wildfire erosion may cause challenges for drinking water treatment plants and the control of the formation of toxic DBPs. Both S-plots and A-plots increased TDN concentrations which may lead to the formation of nitrogen based DBPs and challenge the drinking water treatment. The movement of burnt soil and ash into the downstream waterbodies may increase the turbidity to extents that can be harmful for fishes and other aquatic animals and increase the cost of water treatment. However, the dilution and buffering of runoff water with the background water quality of the streams will govern the overall impacts of post-wildfire erosion on aquatic life and water treatment processes.

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