

Article

Persistence of Soil Water Repellency After the 2022 Bolt Creek Fire

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Abstract

Wildfire ash and water-repellent soil are new materials that are formed after a wildfire that change the mechanical and hydraulic behavior of wildfire-burned slopes. Wildfire ash is known to be typically hydrophilic and to retain water, whereas the water-repellent soil layer acts as a hydraulic barrier. However, there is limited in situ soil water content data to understand the short- and long-term impacts of wildfire ash and a water-repellent soil layer on the hydromechanical behavior of burned slopes. This study investigates the trends in water content of wildfire ash, water-repellent soil, and subsurface soil after the 2022 Bolt Creek Wildfire near Skykomish, WA. The ash deposit averaged 10 cm, with a maximum 30 cm thickness in channels immediately after the fire, which allowed the in situ measurement of ash water content. Soil water content sensors were installed in the ash and subsurface soil layers, and changes in the water content were monitored for a year after the fire. The surface ash layer was above a thin (<1 cm) water-repellent soil layer, which was followed by the soil that did not show any apparent effects from the fire. The results showed a reduction in ash thickness and the persistence of the water-repellent layer over a year.

Keywords: soil water repellency; wildfire; ash

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1. Introduction

Wildfires create new materials on burned hillslopes, such as wildfire ash and water-repellent soil. After a wildfire, wildfire ash is deposited on the soil surface and can contain different minerals, including organic and inorganic (i.e., calcium, potassium, magnesium, phosphorus, aluminum, iron) constituents, e.g., [1,2]. Wildfire ash can have different colors, densities, and quantities in a post-wildfire environment, depending on the fuel load, mineral composition, and combustion completeness, e.g., [3–5]. The thickness of the ash layer can vary from less than a few cm to up to 20 cm, e.g., [3,6,7]. Water-repellent soils are commonly seen after a wildfire, e.g., [8–11]. Water-repellent soil forms when hydrophobic compounds in organic materials that burn and volatilize during the fire travel along the subsurface, condense, and coat the soil particles [12]. Water repellency depends on many factors, including the water content, soil type, fire intensity, and fire duration [12–15].

Wildfire ash and water-repellent soil can change the hydraulic and mechanical behavior of wildfire-burned slopes. Wildfire ash is typically hydrophilic, can retain water, and reduce infiltration and runoff, e.g., [16,17]. The reduction in infiltration and runoff

may result in a short-term reduction in runoff-dominated erosion until the ash is saturated, e.g., [18], which can result in a lateral flow in the soil–ash interface, particularly if the underlying soil layer is water repellent, e.g., [19]. Water-repellent soils prevent vertical infiltration. Additionally, fire-affected soils, regardless of the presence of condensed organic compounds, may behave as water repellent immediately after a wildfire until soil suctions decrease below approximately 10^3 kPa [20]. These hyper-dry soils can adsorb water vapor but show near-zero infiltration until the water-retention mechanism transitions from adsorption to capillary condensation, e.g., [20–22].

Wildfire ash is known to be quickly transported by wind or with rainfall and subsequent runoff, e.g., [23–25]. However, the timeline largely depends on wind speed, rainfall runoff, erosion, and ash amount (i.e., ton ha^{-1}). Ash redistribution can be spatial or vertical due to raindrop impacts, bioturbation, or freeze–thaw cycles, e.g., [24,26,27]. The movement of ash into soil also changes the soil properties, including soil water repellency, water retention, water vapor sorption, and saturated hydraulic conductivity, e.g., [21,28–31].

Soil water repellency can show temporal fluctuations after a wildfire, regardless of the presence of condensed organic compounds, because of the changes in soil moisture. For example, a site burned by the 2018 Williams Flats Wildfire showed the highest water repellency at the soil surface in July, where the ambient temperature was the highest and where no rainfall was recorded [32]. While the temporal changes in soil water repellency do not necessarily show a trend for surface soils, the persistence of water repellency of the surface soil is often attributed to the vegetation type, e.g., [33]. For the subsurface soils, limited studies showed that water repellency is persistent. For example, Huffman et al. [34] found varying levels of persistent soil water repellency in the subsurface soil (up to 6 cm) 22 months after a wildfire in Colorado in a pine forest. Rodriguez-Alleres et al. [15] found varying levels of persistent water repellency in the subsurface soil (up to 40 cm) 15 months after a wildfire in a pine forest in Spain. There is no continuous in situ soil water retention data to understand the impacts of wildfire ash and water-repellent soil layers on the hydromechanical behavior of burned slopes, particularly for fires in wetter climates that historically did not have many wildfires and, therefore, have high fuel load and ash amounts (i.e., ash thickness).

This study investigates the trends in water content of wildfire ash, water-repellent soil, and subsurface soil after the 2022 Bolt Creek Wildfire near Skykomish, WA. The ash deposit at the site reached up to 30 cm in thickness in valleys immediately after the fire, and the large amount of ash allowed the in situ measurement of ash water content. The surface ash layer, which showed a layered structure, was followed by a thin water-repellent soil layer (<1 cm), followed by the subsurface soil that did not show any apparent effects from the fire. The properties of the ash layers were analyzed to understand the characteristics of the layered ash formation after the wildfire. Soil water content sensors were installed in the ash, and the subsurface soil layers and water content were monitored for a year after the fire. The results showed the mobilization of the ash layer and the persistence of the water-repellent layer over a year.

2. Methods and Materials

2.1. Study Site and Instrumentation

The 2022 Bolt Creek Fire started on 9 September 2022, 2.4 km north of Skykomish, WA. The wildfire burned 4660 ha of land. Burned Area Emergency Response (BAER) teams classified 895 ha as unburned or underburned, 1500 ha as low soil burn severity, 1535 ha as moderate soil burn severity, and 730 ha as high soil burn severity (BAER report 2022 (unpublished), [35], Figure 1a). The LANDFIRE Existing Vegetation Type (<https://www.landfire.gov/viewer>, accessed on 23 February 2024) indicates that burned

vegetation was mainly silver fir (*Abies amabilis*), Douglas fir (*Pseudotsuga menziesii*), Western hemlock (*Tsuga heterophylla*), and mountain hemlock (*Tsuga mertensiana*). A slope with a 25° slope angle was selected for this study. The selected study site was at the intersection between low and moderate soil burn severity areas (Figure 1a).

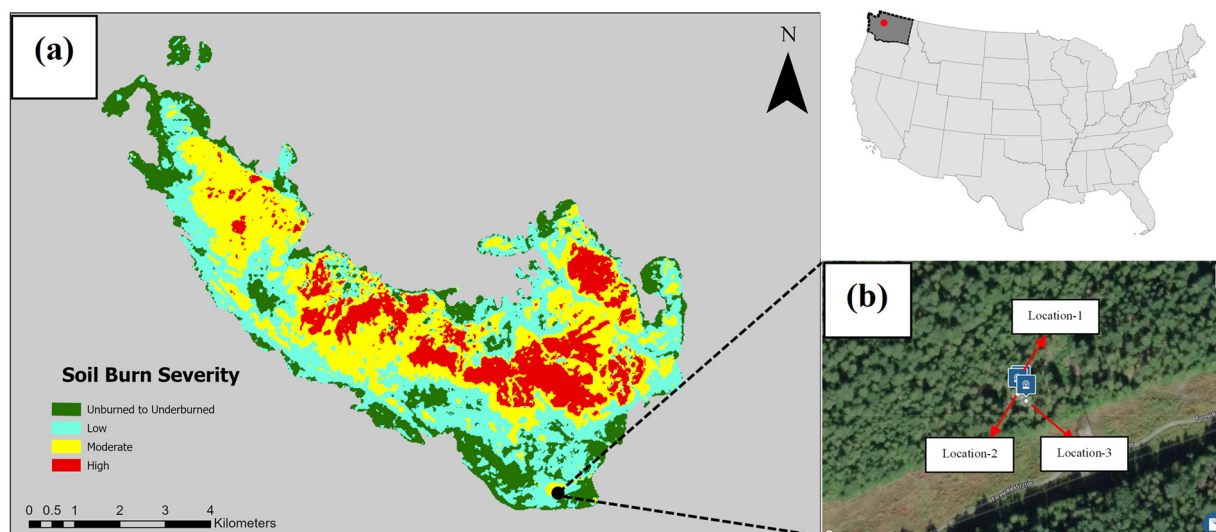


Figure 1. (a) Soil burn severity after the 2022 Bolt Creek Fire, and (b) sensor locations in a pre-fire image.

The study site was first visited between 27 and 31 October 2022. The ash and soil profile showed a 2 to 3 cm thick surface ash layer, consisting of a mixture of orange, white, black, and light gray ash, followed by a 7 to 8 cm thick subsurface ash, consisting of dark gray ash (Figure 2a). The ash layers were underlain by a light-colored water-repellent soil layer, followed by the light brown native soil. The layering of the ash profile was consistent throughout the site but showed varying thicknesses, where the thickness of the ash layer reached up to 30 cm in channels. The unusually high thickness of the ash layer was because the region has an oceanic climate and had not experienced a wildfire recently [36]. According to the Washington Geospatial Open Data Portal, the site has not experienced any large fires for at least 49 years. The wet climate and lack of a wildfire history led to a high fuel load and corresponding ash thickness at the site.

Samples of surface ash, subsurface ash, water-repellent soil, and native soil were collected using a trowel. The site was visited approximately a year later, between 22 and 25 September 2023. Ash was still present on the soil surface; however, the thickness of the ash layer was approximately 3 to 4 cm less compared to immediately after the fire (Figure 2b). Nearly all the surface ash had moved by the end of the year. The majority of the site was covered with a 6 to 7 cm thick layer of subsurface ash. The 2 to 3 cm thick layer of water-repellent soil was still present at the site, followed by the light brown native soil. Samples of subsurface ash, water-repellent soil, and native soil were collected using a trowel during the second field visit.

The precipitation data were acquired from the closest weather station, which was around 19 km away from the study site (Skookum Creek, WA weather station data, <https://scacis.rcc-acis.org> (accessed on 5 January 2024). The elevation of the weather station is 1009 m, while the elevation of the study site is around 500 m. The precipitation data were acquired from 1 November 2022 to 24 September 2023.

Volumetric water content sensors (TEROS 11, Meter Group, Pullman, WA, USA) were first installed in various ash and soil layers for short-term data collection during a

2-day rainstorm. The sensors were placed by pushing the needles of the sensor through the targeted layer. The water content sensors were placed on the surface ash layer by penetrating the sensors through the ash without opening any trenches. Small trenches were cut with a trowel for the other layers, and the sensors were placed. After the installation of each sensor, the same soil was placed back in the order it was taken while opening the trench to maintain the original profile. The sensors were connected to ZL6 data loggers (Meter Group, Pullman, WA, USA). At the end of 2 days of data collection, each sensor was removed carefully with a trowel, and the locations of the sensors were visually validated.

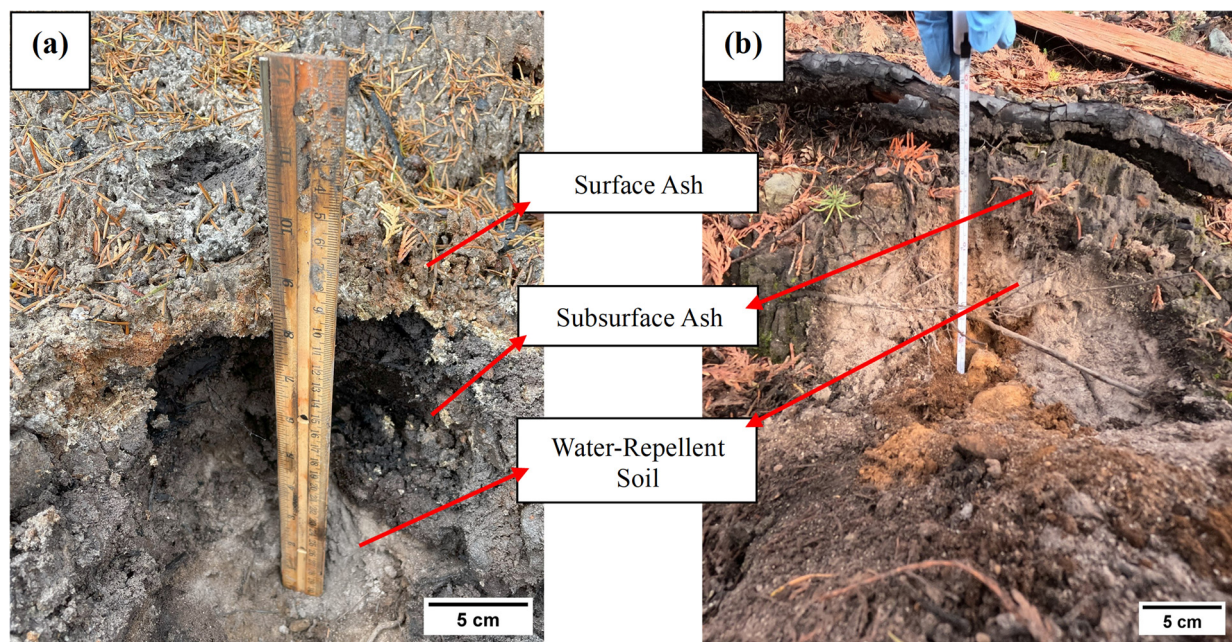


Figure 2. Ash profile (a) immediately after the wildfire and (b) one year after the wildfire.

After the short-term data collection, a total of six volumetric water content sensors were installed at different locations throughout the study site for long-term data collection. Three of these sensors were placed on the subsurface ash layer, and the other three were placed in the soil layer. The sensors were approximately 10 m away from each other. The same procedure for short-term sensor instrumentation was followed; small trenches were cut, the sensors were placed, the soil and ash were placed back into the opened trenches to maintain the original profile, and then the sensors were connected to the data loggers. Both ash and soil sensors were instrumented approximately within the upper 5 cm to 10 cm of their respective layers. The long-term field volumetric water content data were collected from 1 November 2022 to 24 September 2023. The sensor placements were named “Location-1, Location-2, and Location-3” (Figure 1b).

2.2. Field and Laboratory Testing

A mini-disk infiltrometer (Meter Group, Pullman, WA, USA) was used to measure the saturated hydraulic conductivity of the surface ash, subsurface ash, and water-repellent soil immediately after the fire. The surface of each ash and soil layer was leveled with a spatula to place the mini-disk infiltrometer. The amount of infiltrated water was measured at 30 s intervals for 15 min or until 100 mL of water infiltrated. The permeability rate was calculated based on the volume of water infiltrated during each 30 s interval. The mean value of the permeability rate was considered as the representative saturated hydraulic conductivity for the corresponding layer. A mini-disk infiltrometer test was performed for each layer. The variation in infiltration from the average of each layer was calculated

through the standard deviation analysis for each layer. The location of each layer was kept at least 1 m apart to eliminate the influence of the infiltrated water from the previous tests. Before testing the subsurface ash and water-repellent soil layers, the upper layers were carefully removed using a trowel. The mini-disk infiltrometer test was also performed one year after the fire on the subsurface ash and water-repellent soil.

The particle size distribution of surface ash, subsurface ash, and soil samples was determined with sieve analysis [37] and hydrometer test [38]. The Atterberg limit test [39] was also performed on the soil samples. The in situ water content of the ash and soil samples was measured using bulk samples collected in sealed sample bags. The water content samples were collected when there was no rainfall or downward flow of water and within an hour to eliminate any changes in the water content. The collected samples were transported to the laboratory, and the water content was measured by oven-drying the samples at 105 °C [40]. The organic contents of the soil and ash were measured for the samples collected both immediately after the fire and one year after the fire by conducting the loss on ignition test, as explained by [41]. The oven-dried (105 °C) samples were kept in a furnace for four hours at 550 °C. The fraction of difference in mass before and after the heating in the furnace to the oven-dried mass is reported as organic content.

The mineral composition of the ash and soil samples was analyzed through X-ray diffraction (XRD) analysis. The XRD of the surface and subsurface ash samples was analyzed using a Rigaku SmartLab X-Ray Diffractometer (North Carolina State University, Analytical Instrumentation Facility, Raleigh, NC, USA) between the 20° and 80° scan range and by using 0.02° scan steps. The XRDs of the water-repellent soil and the soil samples were analyzed using the Panalytical X'Pert Pro X-ray Powder Diffractometer (University of California, Los Angeles, J.D. McCullough X-ray Facility, Los Angeles, CA, USA) between the 20° and 80° scan range and by using 0.06° scan steps.

Water droplet penetration time (WDPT) tests [42] were conducted in the laboratory on the ash and soil samples collected from the site during both visits. Testing was done in situ water content and oven-dry (105 °C) conditions to test both the actual water repellency (in situ water content) and potential water repellency (oven-dried, [43]). The soil or ash surface was leveled, and 16 equally spaced water droplets were placed on the surface as described in [44]. The water repellency was classified according to [45,46]. The samples with WDPT more than 20 min were classified as extremely repellent.

The cation exchange capacity (CEC) of the ash and soil samples was determined by the ammonium displacement method [47]. The 1 M KCl extract was analyzed via the salicylate method (EPA Method 350.1) using high-range nitrogen “Test ‘N Tube” vials (Hach Co.: Method 10031, Loveland, CO, USA) by using a spectrophotometer. Two replicates were tested for each ash and soil sample collected immediately after the fire.

The specific surface area (SSA) of the ash and soil samples immediately after the fire was measured with a single-point measurement method, as described in [48]. Relative humidity (RH) chambers were prepared at 34% RH using a saturated MgCl₂ solution. Oven-dried (105 °C) ash or soil samples (2 g ± 0.1 g) were placed in the headspace of the MgCl₂ solution and equilibrated at 20 °C for 14 days. The difference between dry mass and equilibrium mass was reported as the adsorbed water mass. The uncorrected SSA (m²/g) and corrected SSA (SSA*) were calculated by using [49] Equations (1) and (2).

$$SSA = \frac{X(1 - RH)}{M_i} N \times A_i \quad (1)$$

$$SSA^* = SSA + \gamma SSA \quad (2)$$

where X is the gravimetric water content (g/g), M_i is the molecular mass of water (18.0 g/mol), N is Avogadro's number ($6.023 \times 10^{23} \text{ mol}^{-1}$), A_i is the surface area covered

by one sorbate molecule ($\sim 10.8 \times 10^{-20} \text{ m}^2$), and γ is the correction factor (0.060 for adsorption-based measurements). The corrected SSA (SSA*) was used for further analysis and comparison.

3. Results and Discussion

3.1. Soil and Ash Characterization

The properties of the surface ash, subsurface ash, and native soil samples varied significantly from each other in terms of particle size, organic content, and mineral composition. The soil consisted of 83% sand, 13% silt, and 1% clay-sized particles (Figure 3). According to the USCS soil classification system [49], the soil was classified as silty sand (SM), and according to the USDA soil classification system, the soil was classified as sand. The finer particle size of surface ash was higher than that of the subsurface ash, and the ash layers had finer particle sizes than the soil layer. The fine content of surface ash and subsurface ash was 41% and 29%, respectively. The surface ash consisted of 59% sand-sized particles, 28% silt-sized particles, and 13% clay-sized particles. The subsurface ash consisted of 71% sand-sized particles, 26% silt-sized particles, and 3% clay-sized particles.

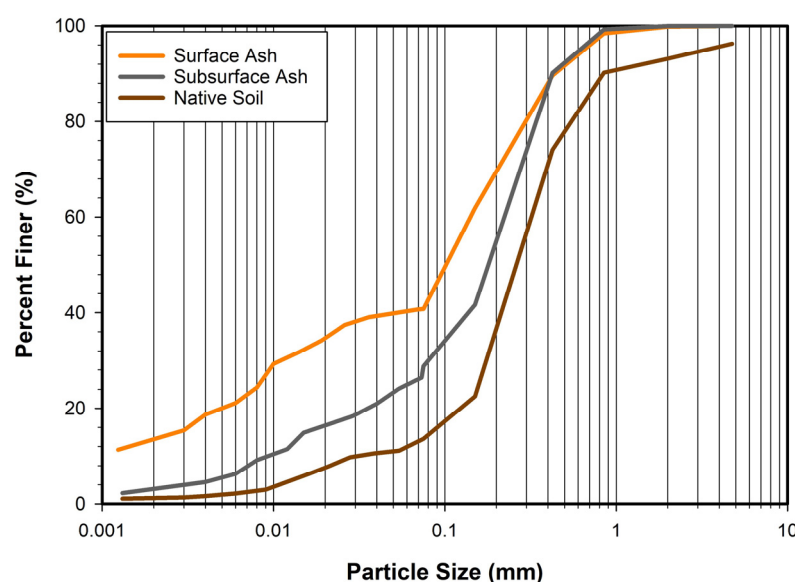


Figure 3. Particle size distribution of ash and soil samples.

The X-ray diffraction analysis showed that the surface ash consists of calcite, quartz, iron oxide, and albite, and the subsurface ash mainly consists of quartz and albite (Figure 4). The soil layers also mainly consisted of quartz and albite. Past studies also showed that quartz and albite are dominant minerals in wildfire ashes, e.g., [1,2,50]. However, in addition to quartz and albite, the surface ash also showed the presence of calcite and iron oxide. The presence of calcite in surface ash indicates higher combustion completeness during wildfires [3]. The surface ash consisted of lighter-colored ashes, which indicate higher combustion completeness [3,5]. However, the orange and black ashes found in the surface ash are associated with the presence of iron oxide, which indicates low combustion completeness [3]. The heterogeneity in the ash layer reflected varying levels of combustion completeness throughout the site.

The CEC of the surface and subsurface ash varied in a small range, between 8.7 cmol+/kg (surface) and 6.8 cmol+/kg (subsurface, Table 1). The SSA showed more variation between 8.2 m²/g (surface) and 1.5 m²/g (subsurface). The higher CEC and SSA in the subsurface ash indicated a slightly higher combustion completeness of the surface ash. A higher combustion completeness was associated with an increased amount

of exchangeable cations [51] and an increase in ash micro-porosity due to the formation of carbonates with less packing density [52]. The CEC of the water-repellent soil was comparable to that of the ashes, but the SSA was only $1.6 \text{ m}^2/\text{g}$. In comparison, the SSA of the soil was $22.3 \text{ m}^2/\text{g}$. The significant reduction in the SSA of water-repellent soil indicated that sorption sites in the water-repellent soil were occupied with the hydrophobic substances and, therefore, were not available to water vapor.

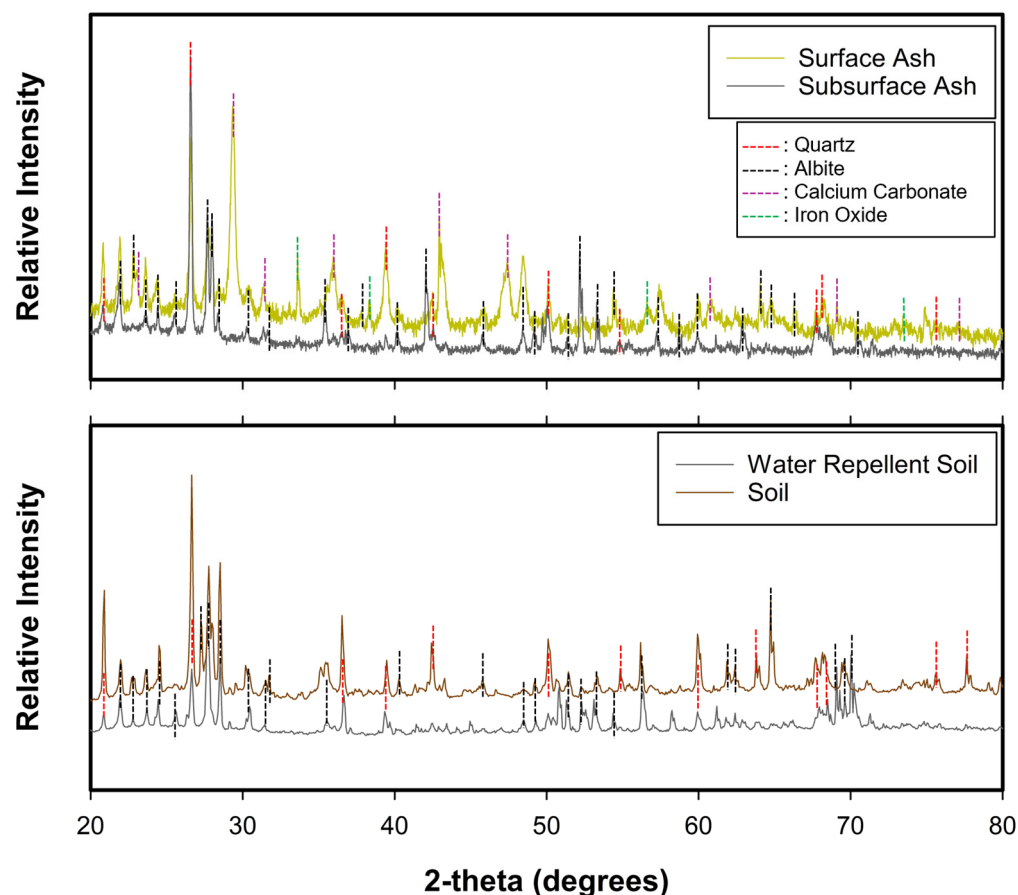


Figure 4. X-ray diffraction analyses of the ash and soil samples.

Table 1. Surface properties and organic content of wildfire ash and soil. * average of three replicates. ^ average of two replicates.

	Cation Exchange Capacity, CEC [^] (cmol+/kg)	Specific Surface Area, SSA (m^2/g)	Organic Content *, Immediately After (%)	Organic Content, One Year After (%)
Surface Ash	8.7 ± 0.72	8.2	4.5 ± 0.08	---
Subsurface Ash	6.8 ± 0	2.5	1.1 ± 0.03	2.2 ± 0.06
Water-Repellent Soil	8.1 ± 0.36	1.6	2.5 ± 0.13	2.3 ± 0.12
Soil	15.2 ± 0.45	22.3	5.8 ± 0.30	9.2 ± 0.29

The subsurface ash had the lowest organic content (1.1% immediately after the fire). The organic content of the soil increased from 6% to 9% one year after the fire. This increase was partly attributed to progressive root decay, as burned tree roots continue decaying in the subsurface over time, e.g., [53].

3.2. Hydraulic Behavior

The WDPT test results showed that the surface and subsurface ash samples were nonrepellent over the year, with an average adsorption time of less than 1 s (Table 2). The water-repellent soil was extremely repellent over the year for both field and oven-dried conditions, where the average adsorption time was more than 20 min. The soil sample immediately after the fire showed slightly repellent behavior at in-situ water content, with an average water adsorption time of 4 s, and a nonrepellent behavior in oven-dried conditions, with an average adsorption time of less than 1 s. The soil sample one year after the fire was nonrepellent in both in situ and oven-dried conditions, with an average adsorption time of less than 1 s. Natural soils can show water repellency due to microbial activity or the presence of organic matter [19]. Moreover, the water repellency of soil depends on the water content, where drier soils show a higher water repellency, e.g., [54,55]. The in situ soil water content immediately after the fire was 0.13 g/g, and one year after the fire, it was 0.30 g/g. The slight soil water repellency immediately after the fire was attributed to the low in situ soil water content.

Table 2. WDPT test results of the soil and ash samples immediately after and one year after the fire. Note: actual is the in situ moisture content, and potential is the oven-dried moisture content.

		WDPT Test Classification	
		Actual Water Repellency	Potential Water Repellency
Immediately after the fire	Surface Ash	Nonrepellent	Nonrepellent
	Subsurface Ash	Nonrepellent	Nonrepellent
	Water-Repellent Soil	Extremely Repellent	Extremely Repellent
	Soil	Slightly Repellent	Nonrepellent
One year after the fire	Subsurface Ash	Nonrepellent	Nonrepellent
	Water-Repellent Soil	Extremely Repellent	Extremely Repellent
	Soil	Nonrepellent	Nonrepellent

The mini-disk infiltrometer tests showed that the saturated hydraulic conductivity of subsurface ash (7.5×10^{-4} cm/s) was greater than the surface ash (1.6×10^{-4} cm/s) but was within the same order of magnitude (Figure 5). The water-repellent soil did not show any infiltration for 15 min during both site visits. The saturated hydraulic conductivity of the subsurface ash increased to 1.3×10^{-3} cm/s one year after the fire and showed a greater variation within the test location compared to immediately after the fire. The increase in saturated hydraulic conductivity of the subsurface ash was attributed to the increase in the organic content (Table 1). An increase in organic content is known to aggregate soil particles and increase the saturated hydraulic conductivity, e.g., [56–58]. The increase could also be due to the erosion of the ash layer over the year or the heterogeneity of the ash layer throughout the site.

3.3. Short-Term Water Content Trends of Ash and Soil

The study site received 366 mm of rainfall in October 2022, and the ash layers were saturated or at near-saturation during the fieldwork (Skookum Creek, WA precipitation station data, <https://scacis.rcc-acis.org>, accessed on 5 January 2024). The short-term volumetric water content (VWC) data showed that the surface ash had a higher volumetric water content than the subsurface ash and soil during the field sampling and testing interval between 29–31 September 2022 (Figure 6). This was in agreement with the higher SSA of the surface ash compared to the subsurface ash (Table 1). On 30 October, the closest rainfall

station (Skookum Creek, WA weather station, <https://scacis.rcc-acis.org>, accessed on 5 January 2024) recorded 102 mm of precipitation. The VWC of the surface ash, which was already saturated prior to installation, remained the same during this rainfall event, at $0.52 \text{ m}^3/\text{m}^3$ (measured gravimetric water content, GWC, of 1.97 g/g). The VWC of the subsurface ash increased from $0.40 \text{ m}^3/\text{m}^3$ (measured GWC of 0.6 g/g) to $0.45 \text{ m}^3/\text{m}^3$. The VWC of the soil did not change during the 2-day period and remained at $0.06 \text{ m}^3/\text{m}^3$ (measured GWC of 0.09 g/g). This indicated the severe hydrophobicity of the water-repellent layer, which was between the subsurface ash and soil. The short-term sensor data and in situ gravimetric water content measurements indicate that rainfall was primarily stored in the surface ash layer and that the surface ash layer had a high water content.

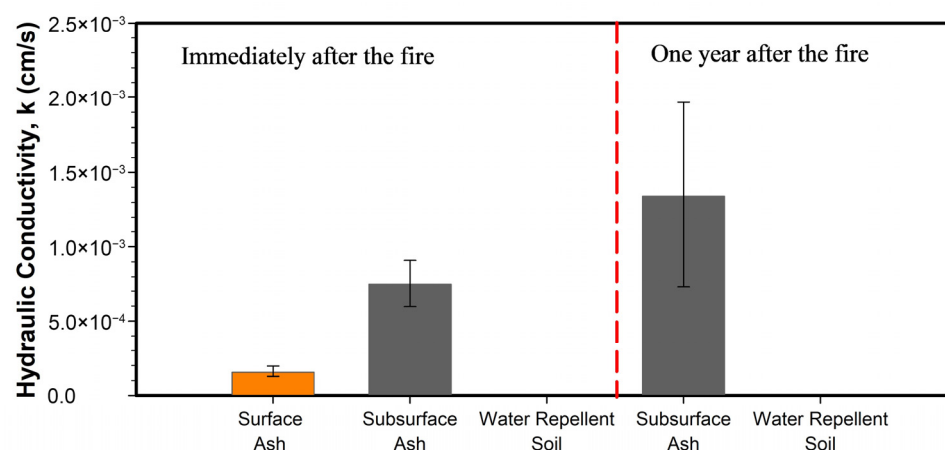


Figure 5. Saturated hydraulic conductivity of ash and water-repellent soil samples (No infiltration recorded in water-repellent soil during the 15 min infiltration test).

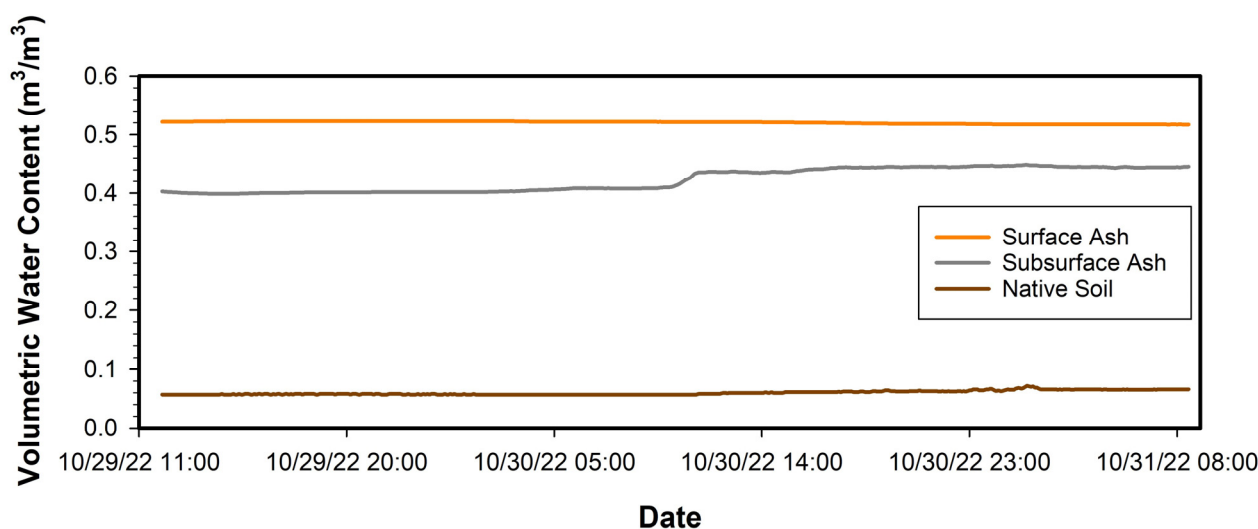


Figure 6. Short-term in situ volumetric water content measurements during an on-site rainfall event of 102 mm.

3.4. Long-Term Water Content Trends of Ash and Soil

The precipitation data showed 2593 mm of precipitation between 1 November 2022 and 24 September 2023 (Figure 7). The cumulative precipitation was 1143 mm during the winter of 2023, 635 mm during the spring of 2023, and 185 mm during the summer of 2023. The precipitation events that are more than 15 mm were named as large storm events for comparison of the precipitation with the volumetric water content data. There was a total of 69 days during which large storm events were observed between 1 November 2022 and

24 September 2023. A total of 29 days were during the winter of 2023, 20 days were during the spring of 2023, and 7 days were during the summer of 2023.

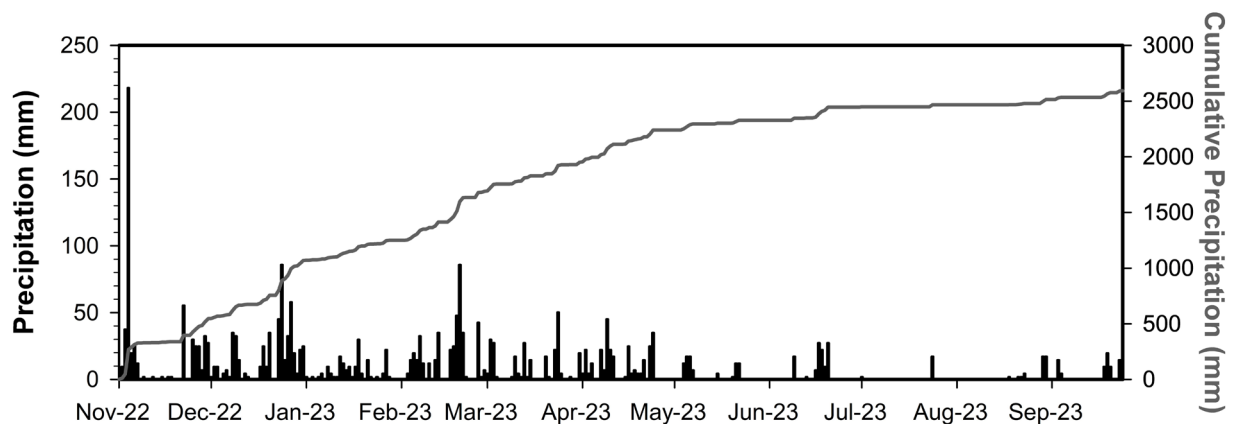


Figure 7. Precipitation data from the closest weather station (Skookum Creek, WA).

The long-term VWC of the subsurface ash and native soil that was measured between 1 November 2022 and 24 September 2023 is shown in Figure 8. The VWC measurements of Location-1 (Soil-1 and Ash-1) were intermittent after August 2023 due to a battery recharge issue.

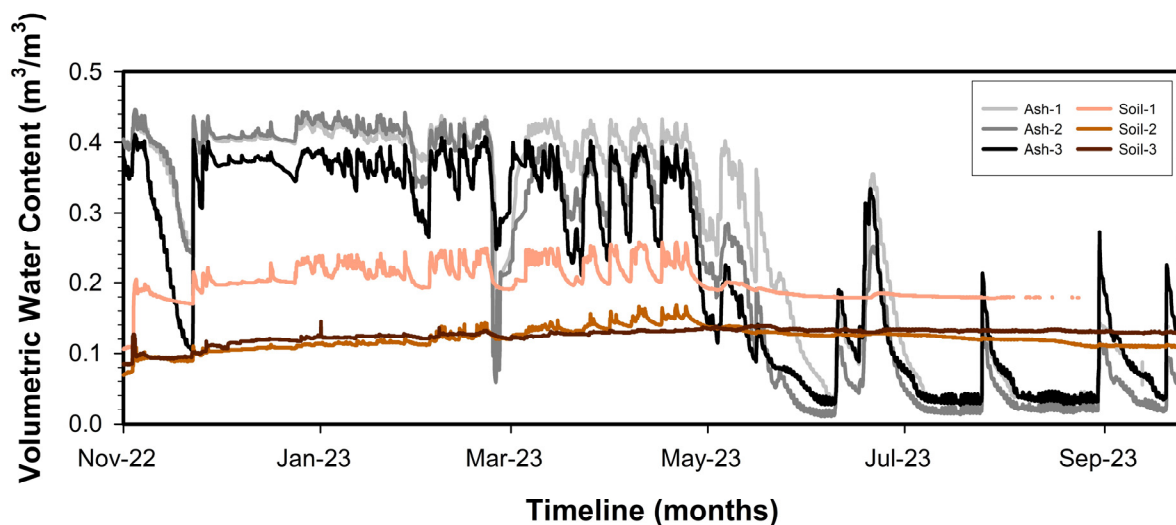


Figure 8. Long-term field volumetric water content measurements.

The VWC of the ash layers showed large fluctuations over the year in response to climate events. The dry period in late November and early December resulted in a decrease in the VWC of ash layers from $0.38\text{--}0.44\text{ m}^3/\text{m}^3$ to $0.10\text{--}0.24\text{ m}^3/\text{m}^3$. The rain events in December increased the VWC back to the initial values. Lower amounts of rainfall between January and February were reflected in the small dips in VWC. In the subsequent days, sunny and low precipitation days reduced the VWC, and high precipitation and cloudy days increased the VWC of the ash layer, with summer months being the driest times. The soil layers, however, did not show the climate-dependent fluctuations to the same extent. The VWC of the soil layer at locations 2 and 3 remained relatively constant, between $0.09\text{ m}^3/\text{m}^3$ and $0.13\text{ m}^3/\text{m}^3$ throughout the year. The VWC of Soil-1 increased on 4 November 2022 after the site received 218 mm of precipitation, stayed higher than the other two locations, and showed more fluctuations than Soil-2 and Soil-3 throughout the year. The higher soil water content at Location-1 could be due to preferential flows that

may cause a subsurface flow path that is observed after wildfires, e.g., [59], or more likely, it is due to the heterogeneity of the ash layer and the discontinuity of the water-repellent layer. Throughout the year, the rain events did not saturate, and the summer months did not dry the soil layers. This indicates the persistence of the water-repellent layer that acts as a hydraulic barrier, continuously preventing infiltration into the soil layer.

4. Conclusions

The ash and soil samples collected after the 2022 WA Bolt Creek Fire were characterized using particle size distribution, CEC, SSA, organic content, hydraulic conductivity, and soil water repellency. The surface ash had a finer particle size and higher CEC, SSA, and organic content than the subsurface ash and therefore maintained a higher water content during an on-site storm event. The ash samples were nonrepellent (<1 s), whereas the water-repellent soil was extremely repellent (>20 min). The extreme water repellency prevented infiltration into the native soil, which maintained a relatively constant water content during both the on-site storm event and for a year after the fire. The subsurface soil showed slightly repellent behavior (4 s) immediately after the fire and nonrepellent behavior (<1 s) a year after the fire in the field conditions, which was attributed to the water repellency due to water content differences in the natural state of the soil. The mini-disk infiltrometer tests showed that the surface ash had lower saturated hydraulic conductivity than the subsurface ash, which was in agreement with the high water content, CEC, and SSA compared to the subsurface ash. The saturated hydraulic conductivity of the subsurface ash increased over time, which was explained by the increase in organic content. The long-term VWC data showed that the VWC of the ash layers fluctuated in response to the climate, whereas the VWC of the soil layers remained relatively unchanged, which was attributed to the persistence of the extremely water-repellent layer in between the ash and soil layers.

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