

Rapid changes in the chemistry of ash and underlying soil layers after pile burning in a subalpine forest

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ABSTRACT

Pile burning is a common practice used to reduce woody debris generated by forestry operations. Combustion of the accumulated fuels generates high temperatures that penetrate into soils, producing highly alkaline, nutrient-rich ash. Little is known about the immediate influence of pile burns on underlying soils or the short-term chemical changes that may regulate post-fire soil microbiome and vegetation recovery. Here we present water-soluble solute concentrations extracted from ash, underlying burned organic matter and mineral soil of six burn piles. Sampling began within days of pile burning and continued throughout the first post-fire year. Fresh pile burn ash had pH of ~10 and was concentrated in plant nutrients (N, P, K) and other solutes derived from combusted wood and organic residue. The pH and solute concentrations in ash and burned soil layers declined significantly within months of burning. However, pH and concentrations of K, Ca, SO₄, and NO₃ in burn pile soils remained elevated relative to nearby unburned areas. Extreme heating and changes in soil structure following pile burns and severe wildfires coupled with the chemical changes we document here will likely have immediate and lasting impacts on soil microbial and vegetation communities. The relatively uniform construction of burn piles and their widespread use creates a useful platform for evaluating the response and recovery of soil properties and processes following severe wildfire across a wide range of forest and soil types and climatic conditions.

Introduction

Wildfire plays an essential role in many of Earth's ecosystems (Bowman et al., 2009; Krawchuk et al., 2009) and terrestrial biota have evolved strategies that allow it to persist, recover or reorganize after this natural disturbance (Certini et al., 2021; Falk et al., 2022; Nelson et al., 2022). Combustion alters aboveground vegetation structure and surface organic layers with dramatic consequences for soil properties, microclimate, and other abiotic and biotic factors that influence post-fire regeneration and watershed conditions. Loss of vegetation and exposure of mineral soils during severe wildfires often increase overland flow and erosion with negative impacts on drinking water source areas and aquatic ecosystems (Smith et al., 2011; Paul et al., 2022). Recent increases in wildfire extent and severity (Parks and Abatzoglou, 2020) have prompted concerns about sustaining forest ecosystems (Stevens-Rumann and Morgan, 2019) and long-term water supply from forest watersheds (Robinne et al., 2021).

The ash and charred organic matter generated by severe wildfires typically contain high alkalinity and concentrations of C, N, P and cations (K⁺, Ca²⁺, Mg²⁺) (Bodí et al., 2014; Zeng et al., 2024) that are mobilized by wind and water (Santín et al., 2015; Richardson et al., 2024). Direct deposition of ash during a Colorado wildfire elevated stream K and PO₄-P concentrations, whereas rainstorms the following year mobilized ash and increased dissolved organic C (DOC) and aromatic organic compounds (i.e., BPCAs) in burned watersheds (Thurman et al., 2023; Rhoades et al., 2025a). The composition of ash changes rapidly (Sánchez-García et al., 2023) as soluble ions are leached into soil by infiltrating snowmelt or rainwater, where they may be taken up by biota or chemically altered. The alkalinity and ion concentrations of ash leached by spring snowmelt was 10 % of that observed in fresh ash (Rhoades et al., 2025a). Ash, char and sediment-laden 'blackwater' can overwhelm water treatment operations (Writer et al., 2014), and a better understanding of the chemical composition of these inputs is essential for anticipating post-fire impacts.

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Pile burning is a common tool used in the US to dispose woody debris generated during forest management activities and reduce surface fuel loads, and the practice also creates relatively uniform conditions conducive to studying severe wildfire (Fowler et al., 2024). Piles contain mixtures of wood of varying sizes and dried branches and foliage. In the Rocky Mountain region of the US, piles are ignited when fuels are dry, typically during winter months when snow cover minimizes the risk of fire escape. It should be noted that the high oxygen environment of the uncompacted burn piles differs from the closed pyrolysis systems used to generate biochar.

Common indicators of fire severity, including soil temperature maxima, heating depth and duration (Busse et al., 2005; Busse et al., 2014), the amount and chemical composition of ash and char (Badía and Martí, 2003), consumption of roots, hydrophobicity and loss of soil structure (Keeley, 2009; Parsons et al., 2010) have all been documented within pile burn scars (Hubbert et al., 2015; Rhoades and Fornwalt, 2015; Delac et al., 2021). Temperatures in excess of 400 °C have been recorded at the soil surface within pile burns, with elevated temperature penetrating below 30 cm depth and persisting for several days (Massman et al., 2008; Busse et al., 2013). Though pile burning operations typically avoid surface water, they often occur on sloping terrain where particulate and dissolved chemical constituents of ash and charred materials are susceptible to surface runoff or subsurface transport (Johnson et al., 2011; Hubbert et al., 2015).

In addition to soil heating impacts, pile burning can have lasting effects on interrelated abiotic and biotic soil properties. For example, pile burning impacted the understory plant species composition, growth and nutrient status within a pinyon-juniper woodland for 5 years (Haskins and Gehring, 2004). Both arbuscular mycorrhizae (AM) and ectomycorrhizal fungi (EMF), which form symbiotic relations with understory plant species and coniferous tree species, respectively, were scarce the first year following pile burning in western US conifer forests (Korb et al., 2004; Fowler et al., 2024). These trends have been observed to persist over even greater time periods. For example, the taxonomic diversity of soil EMF was reduced for several decades following pile burning in lodgepole pine forests (Nelson et al., 2024), and soil pH and P were elevated in burn scars that remained unforested for >50 years (Rhoades et al., 2021). It is uncertain if the lasting soil changes result directly from pile burning or from post-fire shifts in soil biota and vegetation.

Previous studies have examined the impacts of pile burning years to decades after combustion (Rhoades and Fornwalt, 2015; Nelson et al., 2024). However, the initial post-fire conditions and subsequent changes will determine the chemical composition of the ash that influences surface water and soil and vegetation recovery. The objectives of this study were to characterize the immediate post-fire chemical composition of ash in burn piles and track ash chemistry and changes in underlying organic and mineral soils over the course of a year. Based on previous post-fire research, we expect that the chemistry of highly alkaline ash and partially combusted organic soil layers to change rapidly after burning. Furthermore, we expect to observe changes in underlying mineral soils that reflect initial heating impacts and subsequent inputs from combusted surface layers. Following the immediate pulse of alkaline, nutrient-rich ash, we hypothesize that the chemistry of the burn pile scars will fluctuate within the range found in unburned soils. The changes in the chemistry of ash and surface layers following pile burning or severe fire will determine the composition of potential inputs to soils and transported to streams.

Methods

The study was conducted in north central Colorado in a lodgepole pine stand (*Pinus contorta* var. *latifolia*) within the Arapaho-Roosevelt National Forests, near the Fraser Experimental Forest (FEF). Mean annual temperature at FEF headquarters (elevation 2725 m) is 0.5 °C, and ranges from averages of −10 °C in January to 12.7 °C in July. Mean

annual precipitation is 610 mm (range 427–902 mm; 1981–2010 data record), nearly two-thirds of which falls as snow. Annual inorganic N deposition averaged 2.6 kg N ha^{−1} in recent years (Argerich et al., 2013). The local area was extensively glaciated and FEF is underlain by metamorphosed rock, most commonly biotite schist and hornblende or calc-silicate gneiss (Shroba et al., 2010). Soils are skeletal, sandy loam Dystric and Typic Cryochrepts (Alstatt and Miles, 1983) with 20–30 % gravel and 30–50 % cobble-sized materials.

We studied six machine-built piles that were constructed in summer 2020 and burned in late January 2022. Piles contained lodgepole pine boles (~20 cm diameter), tops and branches resulting from a roadside harvesting project. A large portion of the piled material consisted of bark beetle-killed pine that had been dead about 15 years (Collins et al., 2012). The diameter and height of the piles averaged 10.9 m (8–15 m range) and 3–4 m, respectively. This was equivalent to 153 m³ and 12 Mg gross pile volume and mass (Wright et al., 2009). Wood in the interior of piles combusted completely, though there was some residual charred wood at the edge of the piles. Soil that was attached to tree root wads or moved by blading operations was mounded near the center of some piles.

Sampling started on February 8, 2022, and continued on monthly intervals through October. A final sample was collected the following year (May 2023) after snowmelt. We sampled ash, burned organic (~2 cm depth) and mineral soil (0–5 cm depth) layers near the center of piles where white ash indicated high temperature combustion (> 400 °C, Ulery and Graham, 1993). The following procedures were used to avoid contamination between layers and consecutive sampling events. On each sample date, a small vertical pit face (~25 cm horizontal; ~5 cm vertical) was prepared with a sharp, flat hand trowel in order to visibly differentiate the sample layers. Samples were removed horizontally, avoiding the boundary between ash, burned organic and mineral soil layers where cross-contamination was likely and, in some cases, visible. The sampling trowel was cleaned with EtOH before each layer was collected. Following ash collection, residual ash was carefully scraped from the surface of the burned organic layer. That layer consisted of partially charred organic matter from accumulated logging debris plus the original forest O-horizon. As described above, residual charred organic matter was also scraped from the surface of the mineral soil before that layer (0–5 cm depth) was collected with a 7.5 cm diameter steel corer. Sample locations were carefully marked and avoided during subsequent events. Unburned samples of forest O-horizon (organic layer) and mineral soil (0–5 cm) were sampled as described above within intact lodgepole pine forest, 100 m from the burn piles.

Prior to chemical analyses, samples were air-dried, then mixed and sieved (2 mm mesh) to remove large char and non-combusted wood from the ash layer and rocks and roots from mineral soil samples. The pH of ash and burned and unburned burned organic and mineral soil layers were analyzed in 1:2 soil to deionized water (DI, < 1.0 µS/cm) slurry after one hour of agitation, then again in a dilute salt solution (0.01 M CaCl₂; Thomas, 1996).

Ash, and burned and unburned organic and mineral soil samples were extracted in deionized water (20 g soil: 100 mL DI) by shaking for 1 hour and then filtered through 0.45 µm mesh membrane filters (Millipore Durapore PVDF). Water soluble cation (Ca²⁺, Mg²⁺, Na⁺, K⁺, NH₄⁺) and anion (SO₄^{2−}, PO₄^{3−}, Cl[−], NO₃[−]) concentrations were determined by ion chromatography (Thermo-Fisher Corporation, Waltham, MA, USA) within 24 h of extraction. Detection limits were 0.01 mg/L for all ions. Analysis of specific conductivity (SC), pH, and acid neutralizing capacity (ANC) via Gran titration were measured on unfiltered subsamples (Mettler Toledo, Columbus, OH, USA). Dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) concentrations were quantitated in filtered extracts using high-temperature combustion catalytic oxidation with infrared detection on a total organic C/N analyzer after 2 M HCl treatment to remove mineral C (TOC-V_{CPN} Shimadzu Corporation, Columbia, MD). Detection limits for DOC and TDN were 0.04 and 0.01 mg/L, respectively.

Statistical and graphical analyses

Seasonal changes in ash and burned organic and mineral soil chemistry were tested using a non-parametric Kruskal-Wallis analysis of variance (SPSS Inc., V. 25 IBM, Chicago, IL, USA). Burned organic and mineral soil from pile burn scars were compared to unburned O-horizon and mineral soils from adjacent areas using a non-parametric Mann-Whitney U test. Where identified in the text, differences among mean values were assigned for p values less than $\alpha = 0.05$. The contribution of dominant anion and cations in wildfire ash and burned organic and mineral soil were compared graphically to unburned organic and mineral soil layers, and subsurface leachate and stream water from adjacent unburned forests (Grapher V. 16.2.354; Golden Software LLC, Golden, CO, USA).

Results

Burn pile ash and burned organic layers were highly alkaline and concentrated in ions derived from combusted wood and organic residue (Fig. 1, Table 1). Our sampling captured short-term changes in the chemistry of the underlying organic and mineral layers associated with pile burning relative to nearby, unburned organic and mineral soil horizons (Fig. 2, Table 2). For some analytes, post-fire changes persisted for the duration of the study.

Potassium (K) and sulfate ($\text{SO}_4\text{-S}$) were the dominant cation and anion, respectively, in fresh ash (Table 1). The maximum concentration of K was an order of magnitude above any other cation and that of $\text{SO}_4\text{-S}$ was more than double any other anion. The ranked abundance of cations in fresh ash ($\text{K} > \text{Mg} > \text{Na} > \text{Ca} > \text{NH}_4\text{-N}$) differed from that in burned organic and mineral soil ($\text{Ca} > \text{K} > \text{Mg} > \text{NH}_4\text{-N} > \text{Na}$), with a notable shift in the relative importance of Ca compared to K. Concentrations of both $\text{SO}_4\text{-S}$ and nitrate ($\text{NO}_3\text{-N}$) in fresh ash were roughly 2 orders of magnitude greater than those in mineral soil. For most solutes, concentrations in fresh ash were higher than burned organic and mineral soil, though calcium (Ca) and orthophosphate ($\text{PO}_4\text{-P}$) were higher in the burned organic layer, and ammonium ($\text{NH}_4\text{-N}$) was higher in both burned soil layers compared to ash.

Ash pH_w (e.g., pH in water) was highest (10.1) on the first date sampled, then declined to around 9 during the summer months and to about 8 in autumn (Fig. 1A). Overall, ash pH_w averaged 8.9, and the highest individual sample was 10.5. Both burned organic and mineral soil pH_w increased from the onset of the study, peaked during the summer months and then returned to levels measured in nearby unburned soils. On average, burned organic layer pH_w increased by 1.4 units from the first sample date to a maximum in August. Burned organic layer pH_w plateaued around 8.4 between May and August before declining; maximum burned organic pH_w was 9.4. Mineral soil pH increased steadily over the course of five months and then declined rapidly. Over the study period, burned organic layer pH averaged > 2 units above that of unburned O-horizon soil (7.7 vs 5.4), though it was 3 units higher during the summer months. Similarly, the pH of burn scar and unburned mineral soil diverged by as much as 3 units, though on average they differed by half of that. Averaged across sample dates, pH in salt (pH_s) was 0.4, 0.4 and 0.6 units lower than pH_w for the ash, burned organic and mineral layers, respectively (data not shown). In contrast, salt depressed the pH of unburned organic and mineral layers by 0.6 and 1.0 units on average. The smaller pH response to salt addition suggests that the higher ionic strength of the burned layers buffered pH changes compared to the low ionic strength soil solution of the unburned soils.

The acid neutralizing capacity (ANC) of ash and burned organic layers were similar (Fig. 1B) immediately after burning. Mineral soil ANC increased slightly during the first two post-fire sample periods, while it decreased by $\sim 50\%$ in the burned organic layer. Both the burned organic and mineral soil layers receded to ANC levels similar to unburned soils in July (5 months post-fire). The specific conductivity

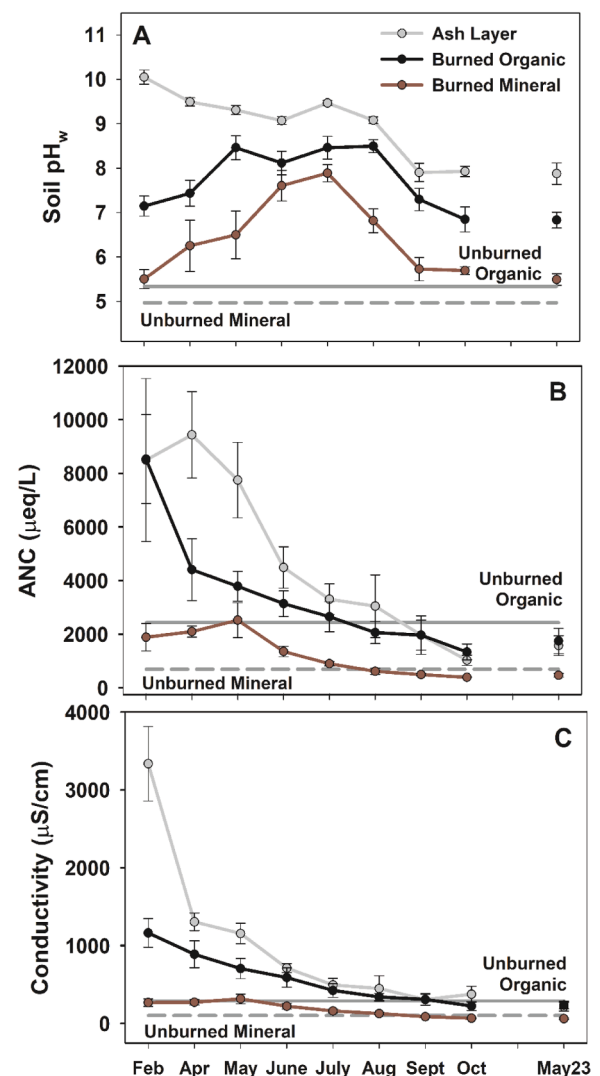


Fig. 1. Ash, burned organic and mineral soil pH A) measured in water, B) acid neutralizing capacity (ANC) and C) specific conductivity following pile burning in a subalpine forest ecosystem in central Colorado, US. Piles were first sampled within days of burning. Data are means of six burn piles with standard error bars. Unburned organic (solid grey line) and mineral soil (dashed grey line, 0–5 cm depth) layers were sampled 100 m from burn piles. Data for the unburned soils are averages of May, August and September samples. Data on the right edge of the graph come from May 2023 samples, fifteen months after pile burning.

(SC) of ash was initially an order of magnitude above that measured in burned soil layers but then declined by $> 60\%$ by April (Fig. 1C). It declined gradually in burned organic layers and both soil layers regained levels in unburned soils within 6 months of pile burning.

Consistent with the pattern observed for specific conductivity (Fig. 1C), high concentrations of most ions measured shortly after burning decreased rapidly in all layers (Fig. 2). For example, SC, K, Ca, and $\text{PO}_4\text{-P}$ in ash decreased by 70 % between the spring and summer dates and $\text{NO}_3\text{-N}$, TDN and $\text{SO}_4\text{-S}$ decreased by 80 %. Similarly, concentrations of Mg, $\text{SO}_4\text{-S}$, Ca, $\text{PO}_4\text{-P}$ and $\text{NH}_4\text{-N}$ of the burned organic layer declined by 60–70 % during that period. The largest change was for DOC which decreased by 80–90 % in all three layers following spring snowmelt. Notable exceptions were for $\text{NO}_3\text{-N}$ and TDN which increased in the burned organic layer, and K that differed little between spring and summer samples.

We also compared ash, organic and mineral soil from pile burns to soil, subsurface leachate and stream water from unburned areas (Fig. 2).

Table 1Initial ion concentrations (mg/L) in ash, burned organic and mineral soil (0–5 cm depth) layers collected on 8 February 2021, within two days of pile burning ($n = 6$).

		Mean	SD	Minimum	Maximum		Mean	SD	Minimum	Maximum
Ash Layer	K ⁺	578.9	336.1	277.3	1107.1	SO ₄ ²⁻ -S	216.5	15.8	199.2	241.2
	Mg ²⁺	83.5	11.8	62.9	97.2	NO ₃ -N	62.4	10.4	50.2	74.0
	Na ⁺	71.9	10.9	61.4	91.6	Cl ⁻	32.6	7.8	22.3	41.5
	Ca ²⁺	65.2	12.0	41.6	75.0	PO ₄ ³⁻ -P	5.9	6.5	2.5	19.0
	NH ₄ ⁺ -N	1.9	1.0	1.0	3.2					
Burned Organic	K ⁺	77.7	86.4	28.2	252.6	SO ₄ ²⁻ -S	34.4	21.8	16.1	75.4
	Mg ²⁺	51.1	21.7	20.9	83.2	NO ₃ -N	10.3	11.6	3.2	32.5
	Na ⁺	3.7	1.6	1.6	5.7	Cl ⁻	8.8	5.4	5.0	18.8
	Ca ²⁺	112.1	69.0	50.0	236.0	PO ₄ ³⁻ -P	7.5	9.1	2.5	25.9
	NH ₄ ⁺ -N	7.8	3.9	3.1	12.1					
Burned Mineral	K ⁺	17.0	7.5	8.7	29.1	SO ₄ ²⁻ -S	2.2	1.6	0.3	4.5
	Mg ²⁺	7.6	5.4	3.2	17.8	NO ₃ -N	5.8	6.8	0.3	14.9
	Na ⁺	3.3	1.0	2.1	4.4	Cl ⁻	7.5	3.1	5.0	13.3
	Ca ²⁺	24.7	19.0	4.0	59.0	PO ₄ ³⁻ -P	0.3	0.4	0.0	0.9
	NH ₄ ⁺ -N	4.7	2.1	3.3	8.8					

Throughout the study, NO₃-N and K concentrations in most ash and burned organic samples exceeded concentration maxima for unburned soils, leachate and stream water. In mineral soil underlying the pile burns, most NO₃-N concentrations (i.e., > median) also exceeded the concentration maxima of the unburned sample types. For K in contrast, only outliers in burned mineral soil exceeded values from unburned samples. Conversely, NH₄-N, PO₄-P, TDN and DOC concentration maxima in unburned O-horizon or mineral soils exceeded those from ash and burned organic and mineral soils. Outliers and 90th percentile concentrations of char NH₄-N, PO₄-P, TDN and DOC, ash PO₄-P and mineral soil DOC exceeded unburned O-horizon or mineral soil. Median concentrations of NH₄-N, PO₄-P and TDN in ash, burned organic and mineral soils exceeded leachate or stream water maxima from unburned areas. Spring season DOC extracted from ash, burned organic and mineral soils was higher than subsurface leachate and stream water from unburned areas, though concentrations in burned and unburned sample types converged during summer and autumn.

Burned organic and mineral soil layers in the burn scars had significantly higher pH and concentrations of water-soluble ions relative to unburned soil (Table 2). Concentrations in the burned soil layers generally decreased in later samples, though differences relative to unburned layers remained evident in many cases. Differences between burned and unburned soils were greatest for SO₄-S, NO₃-N and Ca in both the organic and mineral layers. Concentrations of K, SO₄-S and NO₃-N and pH were significantly elevated in burned layers, both in early and later samples. Analyte concentrations and the increase in burned soils were greater in organic compared to mineral layers, with notable exceptions for NO₃-N and Ca. For example, across both seasons organic and mineral layer soils pH were 2.4 and 1.4 pH units higher than respective unburned organic and mineral soils. Both NH₄-N and PO₄-P were lower in the burned organic layer than unburned O-horizon lower during the later season, though these analytes differ among burned and unburned mineral soils.

Burn pile ash and stream water from unburned forests represent end points for the relative abundance of dominant ions (Fig. 3). For example, K comprised 60 to 80 % of the dominant cations in ash but only 5–11 % in stream water. The contribution of K to dominant cations in unburned organic and mineral soils (50–55 %) was bracketed by the wider range found in char and mineral soil from burn piles (30–70 %). In subsurface leachate from unburned hillslopes, K represented up to 29 % of the dominant cations. In contrast to K, Ca represented < 15 % in most samples, but it was the predominant cation in stream water (70–85 %). Magnesium comprised 10 to 30 % of cations and varied little among sample types, with ash being the most variable. In ash from the first sample date, SO₄ and ANC represented about 60 % and 37 % of the dominant anions (Fig. 3). In all other samples with one exception, ash SO₄ was ≤ 20 % and ANC was ≥ 80 %. Burned organic layer SO₄ fell between 15 and 25 % for most samples, though extreme values spanned

from 7–36 %. In burned and unburned mineral soils, SO₄ ranged from 4–13 % and 1–4 %, respectively. It represented 3–9 % of the dominant anions in stream water and 17 % in hillslope leachate. ANC was the predominant anion in stream water and all other sample types except burned organic layers and ash.

Discussion

Soil heating and ash inputs from pile burning create a relatively well-controlled opportunity to study belowground properties and processes following wildfires of extreme intensity. Complete wood combustion and white ash at the center of the piles, where we sampled, indicate that temperatures surpassed 450 °C (Ulery et al., 1993; Bodí et al., 2014). Soil heating beneath piles of similar size and fuel composition as those we studied typically exceed temperatures lethal to roots (60 °C), seeds (100–125 °C), and alter soil biota and microbial communities (50–400 °C), soil aggregates and C, N and P content (200–500 °C) (Badía and Martí, 2003; Busse et al., 2013; Bodí et al., 2014). For example, in piles of similar diameter as ours, soil temperatures exceeded 400 °C in the surface 2 cm, reached 300–350 °C at 5 cm depth, 100 °C at 15 cm with heat penetrating to 30 cm depth (Jiménez Esquilín et al., 2008; Massman and Frank, 2004).

We documented high alkalinity in fresh ash, as has been observed elsewhere, but we also tracked rapid pH changes in ash and the underlying burned organic and mineral soil layers the months following pile burning (Fig. 1). Increased soil pH due to combustion of organic acids and release of oxides, hydroxides and carbonates and associated cations (Ulery et al., 1993; Certini, 2005) is a common response to severe wildfire and pile burning. The pH of the organic and mineral soil layers collected within days of burning were elevated relative to unburned soils, and it increased an additional 1.5 and 2.5 units for 3–5 months. Ash remaining at the end of our study (15 months after burning) had a pH of 8.0. At that time, charred organic layers and underlying mineral soil pH were 1.5 and 0.5 units above that in unburned organic and mineral soils. Similarly, eight months after pile burning in Montana conifer forests, ash and charred organic layers both had pH around 8.0, and the underlying mineral soil was elevated by 0.5 units (Fowler et al., 2024). Larger pH increases have been recorded after pile burning (Ulery et al., 1993; Korb et al., 2004). For example, at another Colorado location, mineral soil pH (0–15 cm) was 0.6 units higher one week after pile burning and 1.2 units higher 15 months later (Jiménez Esquilín et al., 2008). Soil pH (0–10 cm) was elevated by 2.6 and 1.7 pH units, 6 and 12 months after pile burning in Georgia, respectively, and pH increases extended to lower depths (Creech et al., 2012). Though post-fire pH declines as soluble alkalinity (OH⁻, HCO₃⁻, CO₃²⁻) leaches into the soil (Etiégni and Campbell, 1991) or is eroded by wind or water, calcite, a less-soluble component of wood ash (Ulery et al., 1993; Huang et al., 2024), can contribute to elevated burn scar pH for years (Creech et al.,

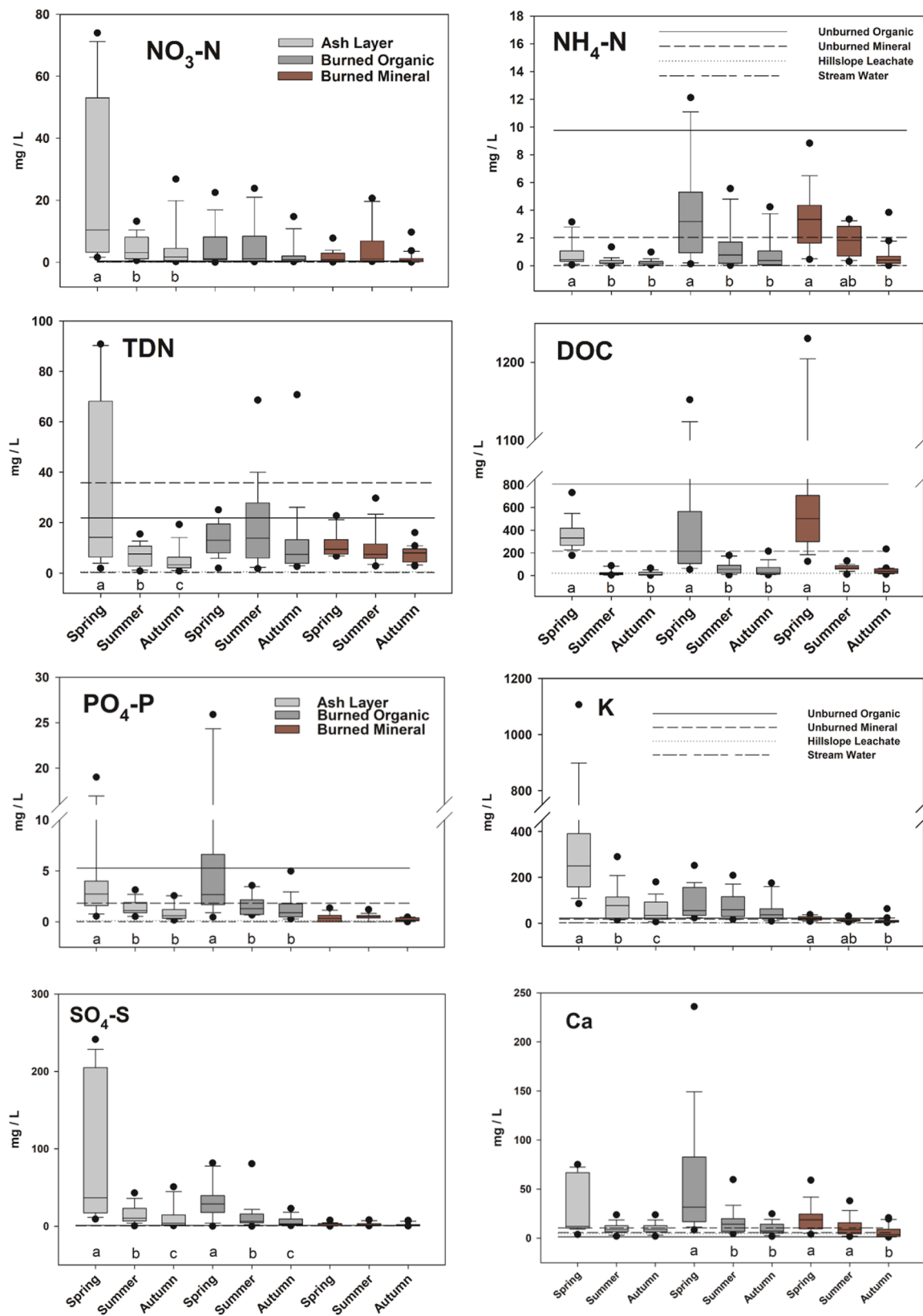


Fig. 2. Nutrient concentrations in ash, burned organic and mineral soil following pile burning relative to maximum values in unburned organic (O-horizon) and mineral soils, subsurface leachate and stream water. Leachate and stream water are from samples collected at the USDA Forest Service Fraser Experimental Forest, adjacent to the pile burn project area. Box plots show median line, 25th and 75th percentiles (box limits), 10th and 90th percentiles (whiskers) and outliers (dots) of 2021 data. Letters indicate that median values differ by $p < 0.05$. Letters denote seasonal differences based on a non-parametric Kruskal-Wallis analysis of variance.

Table 2
Chemistry of the organic and mineral soil (0–5 cm depth) layers following pile burning compared to adjacent unburned soils. Data are means for spring (Feb, May) and autumn (Sept, Oct) samples dates ($n = 12$). For each season, location was evaluated with the non-parametric Mann-Whitney U test.

		pH _w	pH _{salt}	ANC	SC	K ⁺	Ca ²⁺	Mg ²⁺	Na ⁺	NH ₄ ⁺ -N	SO ₄ ²⁻ -S	NO ₃ ⁻ -N	Cl ⁻	PO ₄ ³⁻ -P
Spring	Burned Organic	7.7 **	7.2 **	5589.0	924.0 *	89.0 **	56.7 *	35.2	15.9	4.1	35.8 **	4.8 *	9.7	5.8
	Unburned Organic	5.3	4.6	2955.5	362.3	20.2	11.3	26.6	4.0	7.0	1.1	0.2	9.5	4.4
Autumn	Burned Organic	7.7 ***	7.3 ***	2164.1	359.0	58.5 ***	12.8	12.5	4.6 **	0.9	9.3 ***	3.7 **	4.3	1.2
	Unburned Organic	5.4	4.8	2141.3	244.8	12.8	10.2	18.6	1.7	1.9**	1.1	0.3	4.9	2.5 **
Spring	Burned Mineral	6.1 ***	5.5 ***	2183.0 *	290.3 **	21.8 **	20.2 **	11.7	4.5	3.3	2.6 *	1.6 **	7.4	0.4
	Unburned Mineral	4.8	4.1	745.6	103.9	8.5	2.7	5.8	3.7	1.3	0.3	0.0	6.3	0.2
Autumn	Burned Mineral	6.5 **	6.0 ***	749.4	131.0	23.5	8.7 *	6.1	2.6	1.2	2.1 **	3.4 **	2.5	0.6
	Unburned Mineral	5.1	3.9	636.3	92.9	8.6	3.1	4.8	2.0	0.9	0.4	0.1	5.5	0.6

$p \leq 0.1^*$; $\leq 0.05^{**}$; $\leq 0.005^{***}$.
Units as follows: pH (unitless); ANC ($\mu\text{eq/L}$); SC ($\mu\text{S/cm}$); all others (mg/L).

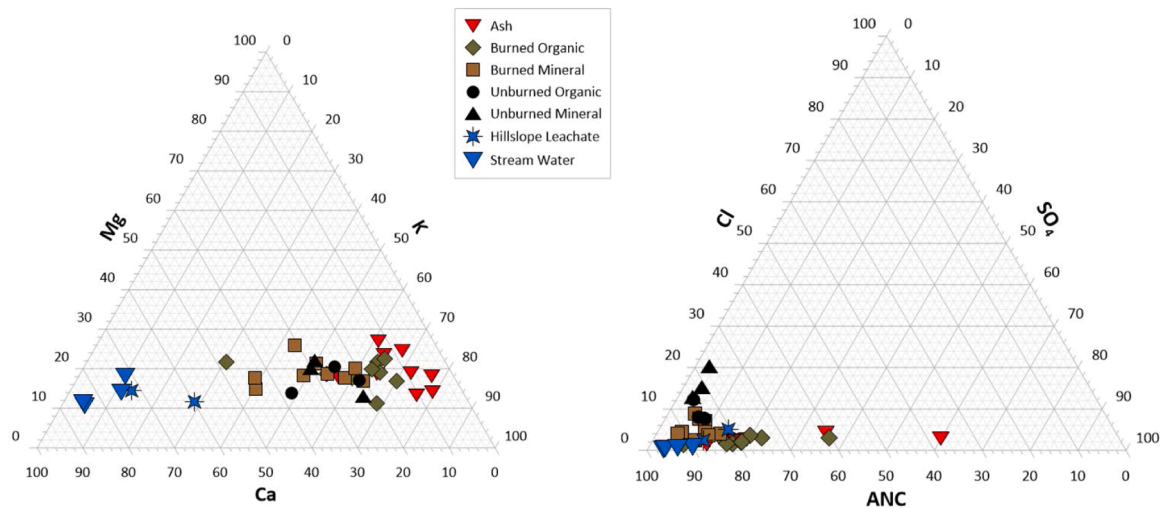


Fig. 3. The proportional representation of dominant cations and anions in ash, burned organic and mineral soil layers from six pile burn scars and adjacent, unburned O horizon and mineral soil, hillslope and stream water. Proportional values of individual ions sum to 100 % in each plot. Hillslope and stream water are from the Fraser Experimental Forest. Hillslope data are mean and maximum concentrations in subsurface leachate draining the upper 1 m of soil of a forested hillslope during the 2022 snowmelt season (i.e., April and May). Stream water data are means of four watersheds sampled weekly between April and October 2021.

2012) to decades (Rhoades et al., 2021).

We measured high initial concentrations of most nutrients and dominant ions in ash, followed by rapid declines over the course of the study (Table 1; Fig. 2). As reported elsewhere (Durgin and Vogelsang, 1984; Etiégni and Campbell, 1991), we found that K was the most abundant water-soluble cation in lodgepole pine ash (Table 1). Potassium was also elevated in fresh ash after wildfires in California, USA, where high concentrations persisted for a few months (Ulery et al., 1993). Similarly, we observed a rapid decline in ash K concentration following spring snowmelt (i.e., 70 %; Fig. 2) although elevated K concentrations persisted longer in the burned organic layer. Calcite (CaCO_3) is another important component of wood ash and a relatively insoluble source of Ca (Etiégni and Campbell, 1991; Ulery et al., 1993; Huang et al., 2024). In the current study (Fig. 3), and wildfires burning in lodgepole-dominated forests (Rhoades et al., 2025a), Ca became the most abundant cation in ash and burned organic layers after more soluble K leached from the surface layers. Elsewhere, soil K levels doubled within days of pile burning and declined within months (Delač et al. 2021); soil Ca, in contrast, increased and remained elevated throughout the 15-month study.

Like other disturbances, severe wildfires and pile burning often increase soil N and P supply and decrease their demand by plants and microbes and thus increase export in stream water (Wan et al., 2001; Johnson et al., 2011; Rust et al., 2018; Moazeni and Cerdà 2024). Inorganic forms of soil N and P are commonly elevated following pile burning (Covington et al., 1991; Korb et al., 2004; Jiménez Esquilín et al., 2008). We found high $\text{NO}_3\text{-N}$ in pile burn ash, charred organic and

mineral soils (Fig. 2) compared to unburned organic and mineral soil layers. Both $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ had much higher initial values in char than in ash. However, with few exceptions, average values fell within the range found in unburned soils over the year of sampling. Earlier research found an immediate post-fire increase in soil $\text{NH}_4\text{-N}$ followed by an increase in $\text{NO}_3\text{-N}$ that was attributed to stimulated nitrifying bacteria activity in the higher pH burn pile soils (Covington et al., 1991). Wood chip mulch applied as a source of labile C to stimulate microbial metabolism effectively reduced excess inorganic soil N following wildfires (Rhoades et al., 2025b) and pile burning (Fornwalt and Rhoades, 2011; Rhoades et al., 2015). Both of these observations suggest that a better understanding of the soil microbial response to extreme and rapidly changing post-fire conditions may have important implications for the biogeochemical processes that regulate nutrient retention, vegetation recovery and surface water quality.

Short-term impacts of pile burning on total soil C and N and organic matter (Wan et al., 2001; Certini, 2005) initiate longer-term changes to colonizing vegetation and soil microbes (Nelson et al., 2024). Much of the impact of severe wildfires is caused by combustion of the O horizon (Parson et al., 2010; Nave et al., 2011) and exposure of mineral soil to erosion (Pierson et al., 2019). Significant short-term losses in total C and N are common after pile burning (Korb et al., 2004; Jiménez Esquilín et al., 2008; Rhoades et al., 2015), though losses from overland flow erosion are less on the flatter, smaller burn scars. However, where pile burn scars are colonized by herbaceous understory plants, soil C and N content have been found to surpass levels in surrounding forests (Creech et al., 2012; Rhoades et al., 2021). Additionally, among other factors,

long-term soil responses vary with plant life history traits (clonal, seeded), the presence of non-native species and soil fauna (Halpern et al., 2014; Fornwalt and Rhoades, 2011).

Pile burning imposes dramatic changes on soils that have implications both above and belowground over short and long-time frames. The relatively uniform nature of pile burning and widespread use of the practice creates an experimental platform to evaluate soil conditions and microbiome responses across forest and soil types and climatic conditions. Combustion-related soil heating represents a severe disturbance that dramatically restructures belowground biotic communities that can favor specific microbial taxa (Glassman et al., 2016; Knight et al., 2024) and altered post-fire resource availability creates conditions that favor other microbial groups (Fierer, 2017). Conversely, colonizing microbes have potential to alter development of burned soils as has been reported following other climate-related stresses and ecosystem disturbances through acidification, nutrient cycling, aggregate formation and other chemical and physical processes (Philippot et al., 2024).

The persistence of herbaceous vegetation in pile burn scars may reinforce some of the soil changes in soil chemistry. Within the aforementioned burn pile chronosequence pH, PO₄ and total C and N were all higher in burn pile soils compared to surrounding unburned forests (Rhoades et al., 2021). Since pH is a strong control on soil microbial communities (Fierer and Jackson, 2006; Bahram et al., 2018) and taxa adapted to more alkaline soil have been shown to be enriched the decade following severe wildfire (Nelson et al., 2024), lasting chemical changes along the burn pile chronosequence would be expected to permeate the microbiome. However, despite persistent changes in soil chemistry, the bacterial community composition and function in these burn piles eventually converged with those observed in surrounding forests (Nelson et al., 2024). This decoupling of the soil microbiome from vegetation highlights open questions regarding how initial post-fire conditions influence longer-term recovery of microbial composition and function.

CRediT authorship contribution statement

Charles C. Rhoades: Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Timothy S. Fegal:** Writing – review & editing, Methodology, Formal analysis. **Julie A. Fowler:** Writing – review & editing, Investigation, Formal analysis. **Banning Starr:** Investigation, Conceptualization. **Michael J. Wilkins:** Writing – review & editing, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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