



ORIGINAL ARTICLE

Stream Chemistry After Colorado's Largest Wildfire: Solute-Specific Responses to Ash and Rainstorms

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ABSTRACT

In 2020, numerous large wildfires, including the largest in Colorado history, burned watersheds that supply agricultural, industrial, and domestic drinking water to both sides of the Continental Divide. Increases in the size and frequency of severe wildfires such as these burning in headwater forests have implications for downstream water supply and aquatic ecosystems across western North America. Here, we evaluate stream water chemistry in 16 tributaries spanning a range of wildfire extent and severity during the first four years after the Cameron Peak Fire. As expected, stream water responses corresponded to the extent

of severe wildfire, though temporal patterns differed among solutes reflecting distinct modes of transport from burned landscapes to streams. Wildfire ash and charred organic matter were alkaline and enriched in numerous water-soluble nutrients. Direct deposition of wildfire ash and smoke elevated stream K, PO₄-P and NH₄-N concentrations prior to significant post-fire precipitation. We observed repeated, short-lived spikes in stream PO₄-P, NH₄-N and turbidity following summer rainstorms, especially the first and second years after the fire. There was a large increase in dissolved organic carbon concentrations following the first intense post-fire rainstorms that more than doubled pre-fire levels and decreased gradually for nearly a year. In contrast, the stream nitrate response lagged until spring snowmelt runoff the second year after the fire, and the solute was less responsive to summer rainstorms. The chemical responses observed in headwater tributaries propagated downstream, where they may influence aquatic ecosystems and water supply to agricultural, residential and other uses. As a whole, these solute-specific patterns improve the understanding of water quality responses to projected increases in extreme wildfires in headwater forests and help prioritize areas that may benefit from post-fire restoration.

Received 14 February 2025; accepted 9 July 2025

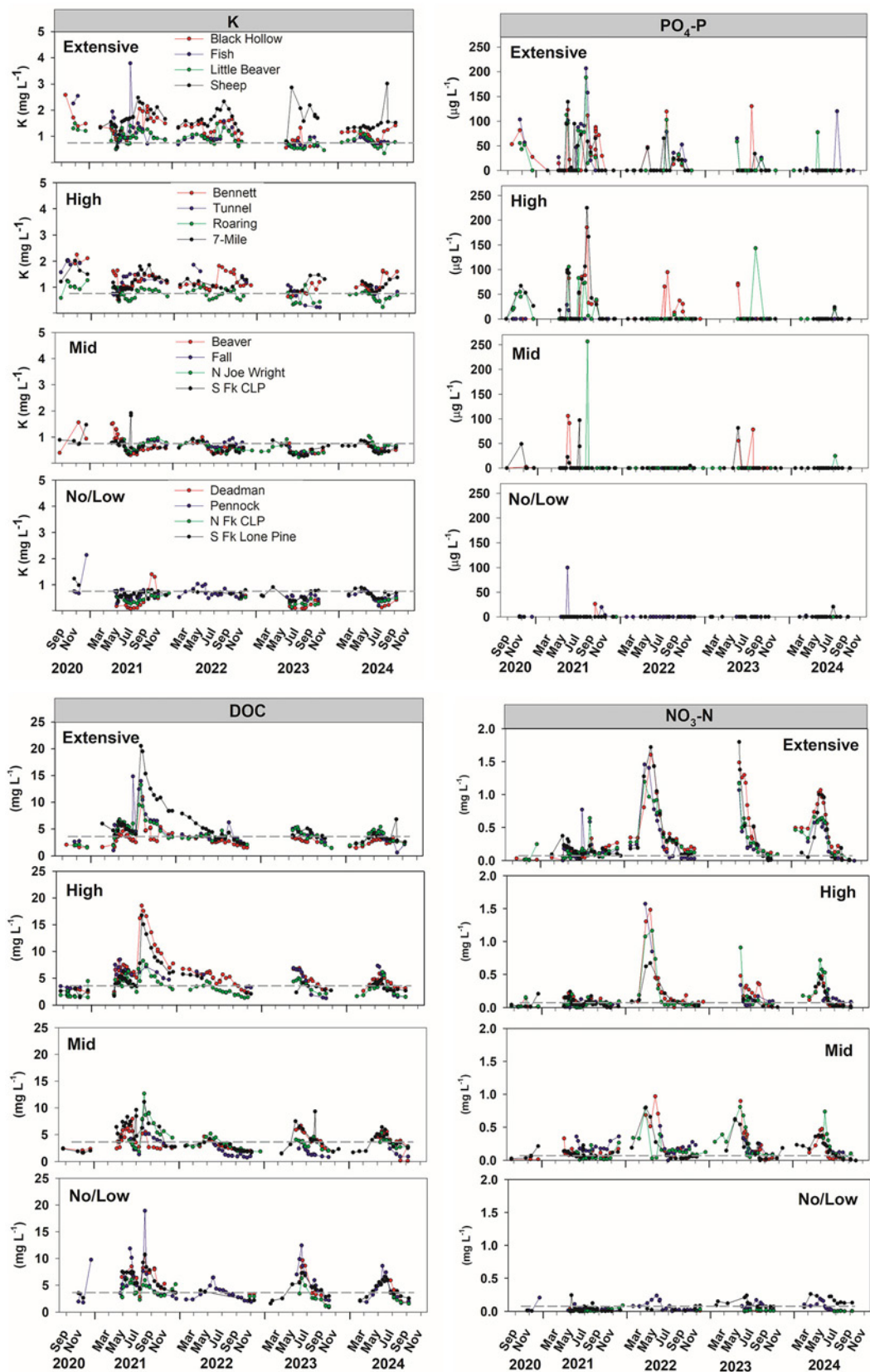
Supplementary Information: The online version contains supplementary material available at <https://doi.org/10.1007/s10021-025-00997-2>.

Authors Contributions Charles C. Rhoades did conceptualization, methodology, formal analysis, resources, writing—original draft, writing—review and editing, supervision, and funding acquisition. Timothy S. Fegel did conceptualization, methodology, formal analysis, investigation, writing—review and editing, and supervision. Allison E. Rhea, Sam Struthers and Katie Willi performed formal analysis, investigation, and writing—review and editing. Jared Heath contributed to validation, and writing—review and editing. Matthew R.V. Ross done conceptualization, methodology, resources, writing—review and editing, supervision, and funding acquisition.

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Published online: 28 August 2025

GRAPHICAL ABSTRACT



Key words: Watershed biogeochemistry; Water quality; Wildfire ash; Nitrate; Phosphorus; Potassium; Carbon; Wildfire severity.

HIGHLIGHTS

- The chemistry of wildfire ash was reflected in storm water in headwater streams.
- Solute concentrations were highest in catchments with extensive severe wildfire.
- Solute-specific temporal patterns tracked the modes of transport from burned landscapes.

INTRODUCTION

Wildfire activity has escalated globally, corresponding to the increase in frequency of severe fire weather (Jones and others 2022). In response to changing climate, fuel accumulation and ignition sources, wildfires burning in high-elevation, headwater forests are more common (Alizadeh and others 2021; Higuera and others 2021). There is evidence that ecosystem effects of climate warming are particularly amplified in high-elevation ecosystems in the Southern Rockies and globally (Pepin and others 2015). Observed and projected increases in wildfire size and severity (Parks and Abatzoglou 2020) coupled with expanding residential development have prompted concerns regarding long-term water supply (Robinne and others 2021) and other ecosystem services from headwater forests (Roces-Díaz and others 2022). Wildfires often negatively impact water source areas, drinking water supply and treatment infrastructure and aquatic ecosystems (Smith and others 2011; Paul and others 2022). Ash, char and sediment-laden 'blackwater' can overwhelm conventional water treatment plant operations, limiting water supply from wildfire-impacted watersheds (Writer and others 2014; Heath and Thorp 2023). Elevated post-fire stream nitrogen (N), phosphorus (P) and carbon (C) alter aquatic food webs (Emelko and others 2016; Erdozain and others 2024) and promote algal blooms that have implications for human safety, river recreation as well as drinking water supply (Hohner and others 2019; Pennino and others 2022).

Wildfires influence watershed biogeochemistry across a range of time frames. The direct consequences of wildfire on watershed conditions and stream water stem from combustion of vegetation

and organic soil layers, deposition of ash, exposure of mineral soils, and alterations in nutrient retention and cycling (Certini 2005; Paul and others 2022). For many chemical constituents, the magnitude and duration of stream water responses relate to the extent of severe wildfire within a given catchment (Richardson and others 2024; Sadler and others 2024). Those associated with surface runoff and erosion are typically triggered by intense rainstorms occurring the first years after a wildfire (McGuire and others 2024). Storm impacts typically abate as surface roughness from herbaceous and understory vegetation returns (Mast and others 2016; Sánchez and others 2023). Conversely, persistent post-fire water quality changes (that is, years to decades) correspond to the extent of forest vegetation loss and its recovery and associated nutrient uptake (Rust and others 2019; Rhea and others 2022). Widespread evidence of slow or sparse post-fire revegetation following recent fires (Millar and Stephenson 2015; Coop and others 2020) adds to concerns about the lasting effects of wildfires on surface water quality.

The impacts of wildfires on surface water vary with the origin, modes of transport and retention of distinct compounds within burned ecosystems (Nunes and others 2018). Combustion of forest biomass and organic surface layers coupled with lower post-fire plant nutrient and water demand elevate soil nutrient content and solute transport to streams via surface and subsurface flow paths (Certini 2005; Murphy and others 2006). Wildfire ash typically contains high concentrations of C, N, P, cations (K, Ca, Mg) and alkalinity (Bodí and others 2014; Sánchez-García and others 2023; Zeng and others 2024). These constituents are released from burned biomass and readily mobilized and transported to streams by wind and water shortly after high-intensity rainstorms (Santín and others 2015; Richardson and others 2024). Aerially deployed fire retardants contain high concentrations of P and N that can elevate these nutrients in soil and stream water (Pappa and others 2008; Marshall and others 2016). Smoke and ash are local and long-range sources of nutrients to burned and unburned watersheds (Spencer and Hauer 1991; Fernandez and others 2024). In addition to water quality threats from increased wildland fire, there is growing concern about mobilization of heavy metals, volatile organics and other compounds following wildfires in areas with historic mining activity (Murphy and others 2020) and current residential development (Whelton and others 2023).

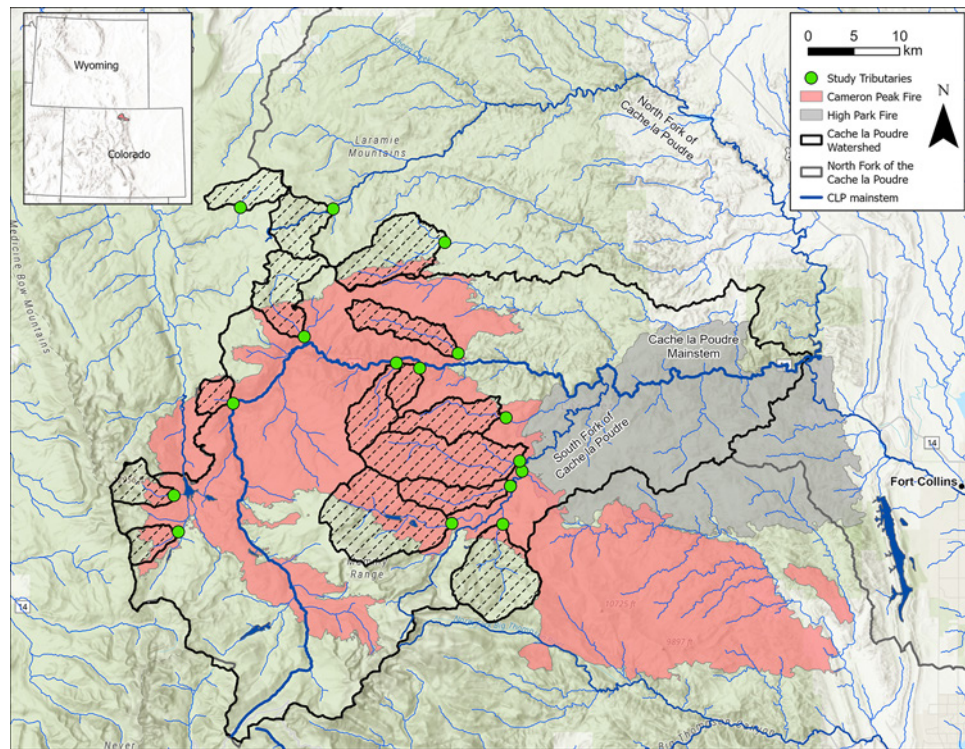


Figure 1. The 2020 Cameron Peak Fire (red) and 2012 High Park Fire scars (gray) in northcentral Colorado, US. The two fires comprise 55% of the forested portion (green) of the Cache la Poudre (CLP) watershed (black outline). Green and blue dots show tributary and mainstem CLP sampling locations, and black hatching denotes the study catchments.

Wildfires exacerbate pre-fire watershed concerns (Pennino and others 2022; Barnard and others 2023). Across the western USA, changing climatic conditions (Hampton and others 2024) and atmospheric deposition have been linked with elevated C, nutrients and harmful algal blooms in water originating in headwater forests (Heath and Thorp 2023). High-elevation fires are likely to add to those stresses, but owing to their relative rarity, post-fire water quality responses are poorly understood. Water utilities, land managers and the public require information to help forecast the impacts of wildfires on water supply and other ecosystem services (Roces-Díaz and others 2022; Carney and others 2025). A better understanding of the magnitude and duration of change following severe wildfire can inform expectations about how high-elevation watersheds may respond to projected increases in wildfire size, severity and frequency and help land managers target areas in need of post-fire restoration.

In 2020, the Cameron Peak Fire (Figure 1), the largest in Colorado's recorded history and other large wildfires burned high-elevation headwater forests (Rodman and others 2022). These fires were

characterized by high-intensity combustion with rapid, wind-driven spread (Hart and Preston 2020) and severe effects on vegetation, soils and watersheds (Coop and others 2022; Cunningham and others 2024). About 40% of the area burned by the Cameron Peak Fire burned at high and moderate severity (BAER 2023). In these areas, > 90% of the vegetation was combusted, O-horizon (that is, litter and duff) was consumed, and mineral soil was exposed to overland flow and erosion (Parsons and others 2010). As opposed to lower-elevation forests where shorter fire return intervals are typical, fires in high-elevation forests are relatively infrequent and their effects on watershed response and ecosystem recovery are less well known (Higuera and others 2021; Clark-Wolf and others 2023).

The primary objective of this study was to characterize tributary solute concentrations in storm and non-storm conditions across a range of burn extent and severity the first four post-fire years, when changes in surface water should be most evident (Rhoades and others 2011; Rust and others 2018). Based on the previous work (Riggan and others 1994; Rhoades and others 2011), we expect catchment-scale water quality responses to vary

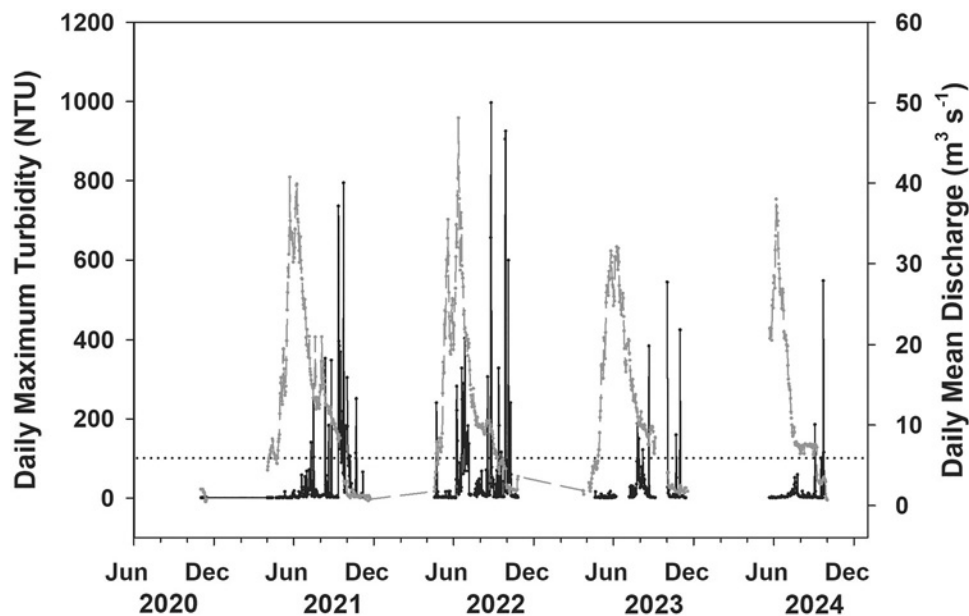


Figure 2. Daily maximum turbidity (black solid line) and mean discharge (gray dashed line) in the Cache la Poudre River following the 2020 Cameron Peak Fire. In situ measurements recorded at 15-min intervals by the City of Fort Collins, CO. The black dashed line shows the turbidity threshold for municipal drinking water treatment (100 NTU). High-intensity rainstorms began in June, and peak turbidity was recorded between August and October. Peak discharge typically occurs in mid-June. Summer storm amount and frequency is presented in SI Table 1.

with wildfire extent and severity. Large storm events following severe wildfires are known to play an outsized role in movement of ash, char and mineral soil-bound solutes (Crandall and others 2021) and cause changes far downstream (Emmerton and others 2020; Nichols and others 2024), and we aimed to sample those events. We hypothesized that initial post-fire storm water would reflect the chemical composition of wildfire ash (Bodí and others 2014) and that storm water would converge with pre-fire conditions as the ash supply is exhausted. We also expected the movement of constituents transported in overland flow (that is, dominant cations) to precede the lagged transport of solutes such as nitrate that typically move along subsurface flowpaths. Our ability to detect post-fire change benefited from pre-fire stream chemistry data collected as part of a citizen-scientist watershed-stakeholder monitoring network. Complementary downstream sampling also allowed us to determine whether these short-term chemical signals of wildfire were detectable at the broader catchments scales that are of interest to water utilities and downstream users. This evaluation should guide expectations about what increases in severe wildfires may mean for headwater forest ecosystems.

METHODS

Site Description

The 2020 Cameron Peak Fire burned 844 km² in the Colorado Front Range, primarily within the Cache la Poudre (CLP) River drainage (Figure 1). Most of the fire was within the Arapaho-Roosevelt National Forest (ARNF), an area that receives eight million visitors per year (USDA 2025). The CLP is Colorado's only Wild and Scenic River, and the ARNF contains four wilderness areas designated to retain the wild nature of the watershed. The CLP supplies water to ~ 0.5 million agricultural, industrial and residential users in northern Colorado (Barnard and others 2023). This involves nine major storage reservoirs, numerous trans-basin diversions and conveyance structures managed by a variety of municipal utilities and private irrigation companies. The mosaic of land-use activities and population pressure found in the CLP are typical of the Colorado Front Range and much of the western USA.

The Cameron Peak Fire began on August 13, 2020, near the headwaters of the CLP and burned eastward until December 2020 with rapid growth during several wind-driven episodes (SI Figure 1). The fire burned 44% of the headwaters of the CLP (Figure 1). The fire scar spanned from 2326 to

Table 1. Sample Tributaries Within and Adjacent to the 2020 Cameron Peak Burn Scar, Colorado (see Figure 1 for Sample Locations)

Severity extent	Watershed	Wildfire severity						
		Area (km ²)	Burn (%)	Hi (%)	Mod	Lo (%)	No	Hi + Mod
Extensive (> 50% Hi + Mod)	Sheep	7	100	14	57	29	0	71
	Little Beaver	47	86	17	51	18	14	68
	Black Hollow	17	88	12	51	24	12	63
	Fish	13	86	11	46	29	14	57
High (25–50% Hi + Mod)	Tunnel*	7	89	12	32	46	11	43
	Bennett	37	70	4	33	32	30	38
	Roaring*	15	57	2	27	28	43	29
	Sevenmile*	19	70	2	25	44	30	26
Mid (< 25% Hi + Mod)	N. Joe Wright*	9	41	13	11	17	59	24
	Beaver	57	43	1	18	25	57	19
	Fall	13	23	8	7	8	77	15
	S. Fk. Poudre*	183	33	2	13	19	67	14
No/Low (< 25% Burned)	S. Lone Pine	22	24	0	13	10	76	14
	Pennock	47	16	0	1	15	84	2
	Deadman	37	0	0	0	0	100	0
	N. Fk. Poudre	19	0	0	0	0	100	0

Burn severity information from USFS Burned Area Reflectance Classification (BARC) conducted using pre-fire and post-fire LANDSAT images.

*Tributaries with pre-fire data (see SI Table S2).

3362 m elevation, which extends from lower montane sage and shrubland and various conifer forest types to the alpine. Lodgepole-pine (*Pinus contorta*) forests comprised 78% of the area burned (LANDFIRE 2019).

Soils are mostly gravelly-cobbly, sandy loam Inceptisols derived from colluvium and residuum weathered from granitic, gneiss, and schist parent material (Shaver and others 1988; Web Soil Survey 2023). The area's Precambrian and Cambrian mineral assemblages are highly felsic, containing high levels of Na and K in igneous granites and metamorphosed gneiss parent material (Abbott 1976) and little Cl. Apatite and fluorapatite are scarce, and P concentrations in local bedrock and resultant soils are very low (Lovering and Goddard 1950).

Precipitation Conditions

Annual precipitation ranges from 430 to 890 mm across the elevation gradient and averages 680 mm across the burn scar (PRISM Climate Group 2024). Though most of annual precipitation is received as snow that infiltrates into soil and is gradually released through subsurface flowpaths, short-duration, high-intensity summer rainstorms falling on exposed soils mobilize ash, charred organic matter

and sediment from burned landscapes. Summer storms elevated turbidity in the CLP above the water treatment threshold (100 NTU) for the City of Fort Collins throughout the study period (Figure 2). The first turbidity exceedance was on July 11, 2021. Shortly after that (July 21, 2021), a storm with rain intensity of 3.7 cm / h (I_{15}) (Kampf and others 2022) generated widespread erosion and debris flows, destroyed several homes, and caused four human fatalities (Prentzel 2021). There were seven consecutive days in September 2021 following storms when raw water intake from the CLP was halted by the City of Fort Collins due to high turbidity. Rainfall during the summer storm season (July–September) was similar between 2021 and 2024, ranging from 115 to 162 mm (Larimer County 2024). However, the number of high-intensity storms (1.5 cm / hr (I_{15})) was lower the second half of the study period (SI Table 1; that is, 7 and 10 storms (> 25.4 mm / hr) in 2021 and 2022 vs. 2 and 1 in 2023 and 2024).

Stream Water Sampling and Analysis

We sampled stream water in 16 tributaries that experienced a range of wildfire extent (0–100%) and severity (Figure 1; Table 1). We partitioned the catchments into groups based on the proportional

area burned at high + moderate severity (Extensive: > 50%, High: 25–50%, Mid: < 25%). Unburned catchments and those with < 25% total burn extent, no high severity and little moderate severity (0–13%) were included in a No/Low class. Consumption of the O-horizon and exposure of mineral soils are relatively similar for areas classified as high and moderate severity (Parsons and others 2020), and their susceptibility to erosion is considered equal during post-fire risk assessments (BAER 2023). We combined high and moderate classes similar to post-fire response teams (BAER 2023) and our earlier post-fire analyses (Rhoades and others 2019a).

In addition to head water tributaries, we sampled three locations along the mainstem of the CLP spanning a 1023-km² drainage area of which 60% burned in the Cameron Peak Fire. Post-fire sampling of tributaries and CLP sites began in spring 2021 and continued through October 2024. Five of the study tributaries were part of a pre-fire stream water monitoring program (2015–June 2020) coordinated by a local watershed-stakeholder group with samples analyzed by our US Forest Service biogeochemistry laboratory (described below). A limited number of tributary sites were sampled during late summer 2020, after the fires had abated in their immediate vicinity.

Water samples were collected weekly (April to June), biweekly (July to October), and monthly (November to March). Samples were collected in HDPE plastic bottles, after triple-rinsing bottles with stream water, then stored cold and filtered through 0.45- μ m pore-size glass fiber filters (Millipore Corp, Burlington, MA). All bottles were triple-washed with deionized water (Specific Conductivity SC < 1.0 μ S cm⁻¹), prior to use. Dominant cation (Ca, Mg, Na, K, NH₄) and anion (SO₄, PO₄, Cl, NO₃) concentrations were determined by ion chromatography (Thermo-Fisher Corporation, Waltham, MA, USA) within 72 h of collection. Detection limits were 0.01 mg L⁻¹ for all ions. Analysis of SC, pH, and acid neutralizing capacity (ANC) via Gran titration was measured on unfiltered subsamples (Mettler Toledo, Columbus, OH, USA). Dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) concentrations were quantitated using high-temperature combustion catalytic oxidation 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⁻¹, respectively. Turbidity was measured using the nephelometric method (APHA 1998; HF Scientific, Inc. Micro 100 Turbidimeter). Total suspended sediment (US EPA 1999; TSS)

samples were collected in 1000-mL HDPE bottles and filtered through 0.7- μ m glass fiber filters (Whatman, Billerica, MA). The TSS filters were dried at 105 °C for 24 h and then weighed.

We used automated samplers (ISCO 6700, Teledyne ISCO, Lincoln, NE) to collect storm water in three extensively burned catchments (Fish, Little Beaver, and Black Hollow). Samplers were connected to stream turbidity sensors (Cyclops-7F, Turner Designs, San Jose, CA) and controlled by data loggers (Campbell Scientific CR800, Logan, UT). Storm water was sampled on 15-min intervals when sensors detected turbidity > 50 normalized turbidity units (NTUs). Samples (1000 mL) were filtered within 24 h of rainstorms and analyzed as described above.

Wildfire Ash Chemistry

To provide context for post-fire changes in stream water, we analyzed the chemical composition of wildfire ash. Fresh ash was sampled in September 2020 prior to significant rainfall, in sites that burned at high severity (n = 10). In June 2021, we sampled residual ash, charred O-horizons and mineral soils following spring snowmelt, but prior to high-intensity rainstorms in lodgepole-pine forests that burned at high severity and similar nearby unburned forests (n = 10). Ash was removed carefully with a brush and dustpan from within a 30 × 30 cm metal sample frame. Sampling tools were cleaned with EtOH between samples. Char derived from combusted O-horizon material and vegetation was then removed. Finally, mineral soil (0–5 cm depth) was sampled with a 7.5-cm-diameter steel corer. Subsamples of each layer were used to quantify pH, ANC, SC water-soluble ions, nutrients, and carbon. Samples were sieved (2-mm mesh), shaken for 1 h in deionized water (20 g sample: 100 mL water) and filtered through 0.45- μ m mesh membrane filters (Millipore Durapore PVDF). Extracts were analyzed as described above.

Statistical and Graphical Analyses

We evaluated solute concentrations in 16 tributaries in and adjacent to the Cameron Peak Fire (Figure 1 and Table 1). Relations between solute concentrations and wildfire extent and the extent of high + moderate severity fire were evaluated using least-squares linear regression (SPSS V. 22, IBM Co., Chicago, IL). Differences among the high severity extent classes (Extensive, High, Mid and No/Low) were evaluated within years using one-way analysis of variance and Bonferroni-adjusted mean separation tests. Constituents leached from

Table 2. Water-soluble Constituents of Ash, Charred O-horizon and Mineral Soil (0–5 cm) in Lodgepole-pine-dominated Forests Burned by the 2020 Cameron Peak Fire and Adjacent Unburned Forests

	Fresh ash		Residual ash		Charred O horizon		Mineral soil		Unburned			
	Mean	Max	Mean	Max	Mean ^a	Max	Mean ^a	Max	O horizon		Mineral soil	
	Mean	Max	Mean	Max	Mean ^a	Max	Mean ^a	Max	Mean	Max	Mean	Max
pH*	8.5	9.2	8.1	8.6	7.5	8.2	6.4	7.1	5.0	5.2	5.2	5.6
ANC**	19,379	27,104	1713	2702	2224	3359	1252	2031	931	954	453	519
SC***	3147	5,016	247	395	309	390	185	306	169	185	81	96
K	490.5	648.4	11.9	33.7	15.2 ^b	48.7	5.5	9.4	17.8	21.3	3.4	4.5
Ca	192.5	422.5	30.5	51.1	36.8	49.6	22.7	42.9	9.4	12.8	11.9	13.9
Mg	87.1	112.8	4.4	7.4	5.7	8.3	3.2	5.7	2.3	6.7	1.1	1.4
Na	4.2	5.5	1.2	2.4	5.7	7.8	4.5	5.6	0.3	0.3	0.4	0.6
SO ₄ -S	120.4	264.0	7.4	12.6	6.4	11.3	5.0	8.0	0.6	1.0	0.8	0.9
Cl	64.5	98.8	4.1	9.4	3.3	4.3	3.7	5.4	2.5	3.2	1.9	2.6
PO ₄ -P	9.8	13.8	1.3	1.8	1.8	2.7	0.1	0.2	2.2	4.4	0.6	0.7
DOC	252.6	404.4	29.5	64.9	33.8	52.5	63.3	102.9	115.2	146.1	42.3	51.8
TDN	21.6	32.1	2.4	9.0	3.4	5.0	5.4	10.8	23.2	24.5	2.2	2.6
NO ₃ -N	3.0	3.2	0.2	0.5	0.4	0.6	0.1	0.2	1.2	1.3	0.8	1.1
NH ₄ -N	1.0	1.8	0.7	1.9	1.4	2.2	1.3	2.0	1.4	1.8	0.04	0.1

Fresh ash was collected in September 2020 before sites received measurable rainfall. Residual ash and underlying char and mineral soil were collected in June 2021 following spring snowmelt, but prior to summer rainstorms. Unburned O-horizon and mineral soils were collected in unburned lodgepole-pine forests within the Cameron Peak burn scar. Data are means of 10 samples per layer and sample type. Concentrations are mg L⁻¹ except where noted.

^ameans of all constituents differed between burned and unburned O horizon and mineral soils ($p < 0.05$), excepted where noted by 'b'

*unitless; **μeq/L; ***μS/cm.

burned and unburned burned and mineral soils were compared with Tukey's t-tests. Levene's statistic was used to test for homogeneity of variance and normality, and unequal variances were log-transformed if needed before statistical analysis. Pre-fire stream chemistry from tributaries, the main stem CLP, and the 16 post-fire tributaries, as well as storm and non-storm data, were compared using nonparametric Kruskal–Wallis analysis of variance. Where identified in the text, differences among mean values were assigned for p values less than $\alpha = 0.05$. When analyses were conducted within seasons, they were differentiated as follows: winter (January, February, March), spring (April, May, June), summer (July, August, September) and autumn (October, November, December). The contribution of dominant anion and cations in wildfire ash and char were compared graphically to storm water and pre-fire stream water (Grapher V. 16.2.354; Golden Software LLC, Golden, CO, USA).

RESULTS

Pre-Fire Stream Water

Seasonal discharge and solute chemistry patterns in the study tributaries (SI Table 1) and mainstem CLP (SI Figure 2) were typical of watersheds with

snow-dominated hydrology. As spring snowmelt progressed, increased stream discharge diluted concentrations of most ions and consequently SC. Notable exceptions were DOC, TDN and NO₃-N that peaked during spring runoff. These constituents are formed by decomposition of soil organic matter and transported to streams along subsurface flowpaths with snowmelt. Pre-fire spring season tributary concentrations were: TDN (0.4 mg L⁻¹), NO₃-N (0.2 mg L⁻¹) and DOC (11.1 mg L⁻¹). Inorganic N comprised 39% of TDN and most of that was NO₃-N (82% vs. 18% NH₄-N). Ortho-P was rarely detectable in pre-fire streams and only during summer months.

Wildfire Ash Chemistry

Ash and char from lodgepole-pine forests that burned at high severity were alkaline and contained high concentrations of soluble nutrients (Table 2). Average pH of fresh ash was 8.5 and reached 9.2. This was > 3 pH units above that measured in unburned O-horizon and mineral soil. Fresh ash had K, Ca and SO₄-S concentrations that were one to two orders of magnitude above those in unburned soils. Water-soluble inorganic N (NO₃-N and NH₄-N) and PO₄-P leached from fresh ash were 4 times higher, and DOC and TDN were 30 times higher than unburned soils.

Table 3. Linear Relation Between Tributary Solute Concentrations and Turbidity to the Extent Wildfire or Extent High + Moderate Fire Severity in Catchments Impacted by the 2020 Cameron Peak Fire

		Wildfire extent			Hi + mod severity extent		
		r^2	slope	p	r^2	slope	p
pH	Mean	0.39	0.004	0.003	0.28	0.01	0.011
	Max	0.25	0.01	0.018	0.17	0.01	0.047
ANC	Mean	0.32	4.55	0.007	0.24	5.74	0.019
	Max	0.39	7.71	0.003	0.27	9.35	0.013
SC	Mean	0.42	0.60	0.002	0.34	0.78	0.005
	Max	0.46	0.99	< 0.001	0.35	1.24	0.004
K	Mean	0.77	0.01	< 0.001	0.68	0.01	< 0.001
	Max	0.49	0.02	< 0.001	0.46	0.02	< 0.001
Ca	Mean	0.33	0.06	0.006	0.27	0.08	0.013
	Max	0.33	0.11	0.003	0.25	0.14	0.017
Mg	Mean	0.43	0.02	0.001	0.33	0.03	0.006
	Max	0.44	0.04	0.001	0.34	0.05	0.005
Na	Mean	0.39	0.02	0.003	0.27	0.03	0.013
	Max	0.54	0.05	< 0.001	0.36	0.06	0.004
SO ₄ -S	Mean	0.60	0.06	< 0.001	0.50	0.08	< 0.001
	Max	0.52	0.14	< 0.001	0.30	0.16	0.008
Cl	Mean	–	–	NS	–	–	NS
	Max	–	–	NS	–	–	NS
PO ₄ -P	Mean	0.57	0.0002	< 0.001	0.49	0.0002	
	Max	0.32	0.002	0.007	0.23	0.002	0.022
DOC	Mean	–	–	NS	–	–	NS
	Max	–	–	NS	–	–	NS
TDN	Mean	0.54	0.003	< 0.001	0.68	0.005	< 0.001
	Max	0.43	0.01	0.001	0.43	0.02	0.001
NO ₃ -N	Mean	0.65	0.003	< 0.001	0.81	0.01	< 0.001
	Max	0.86	0.02	< 0.001	0.78	0.02	< 0.001
NH ₄ -N	Mean	0.23	0.0001	0.021	–	–	NS
	Max	0.36	0.001	0.004	0.35	0.001	0.004
Turbidity	Mean	0.50	0.16	< 0.001	0.58	0.24	< 0.001
	Max	0.20	4.12	0.033	0.30	6.88	0.009

Data are mean and maximum concentrations for all samples collected between 2021 through 2024 in sixteen study catchments (see Table 1).

*NS, not significant.

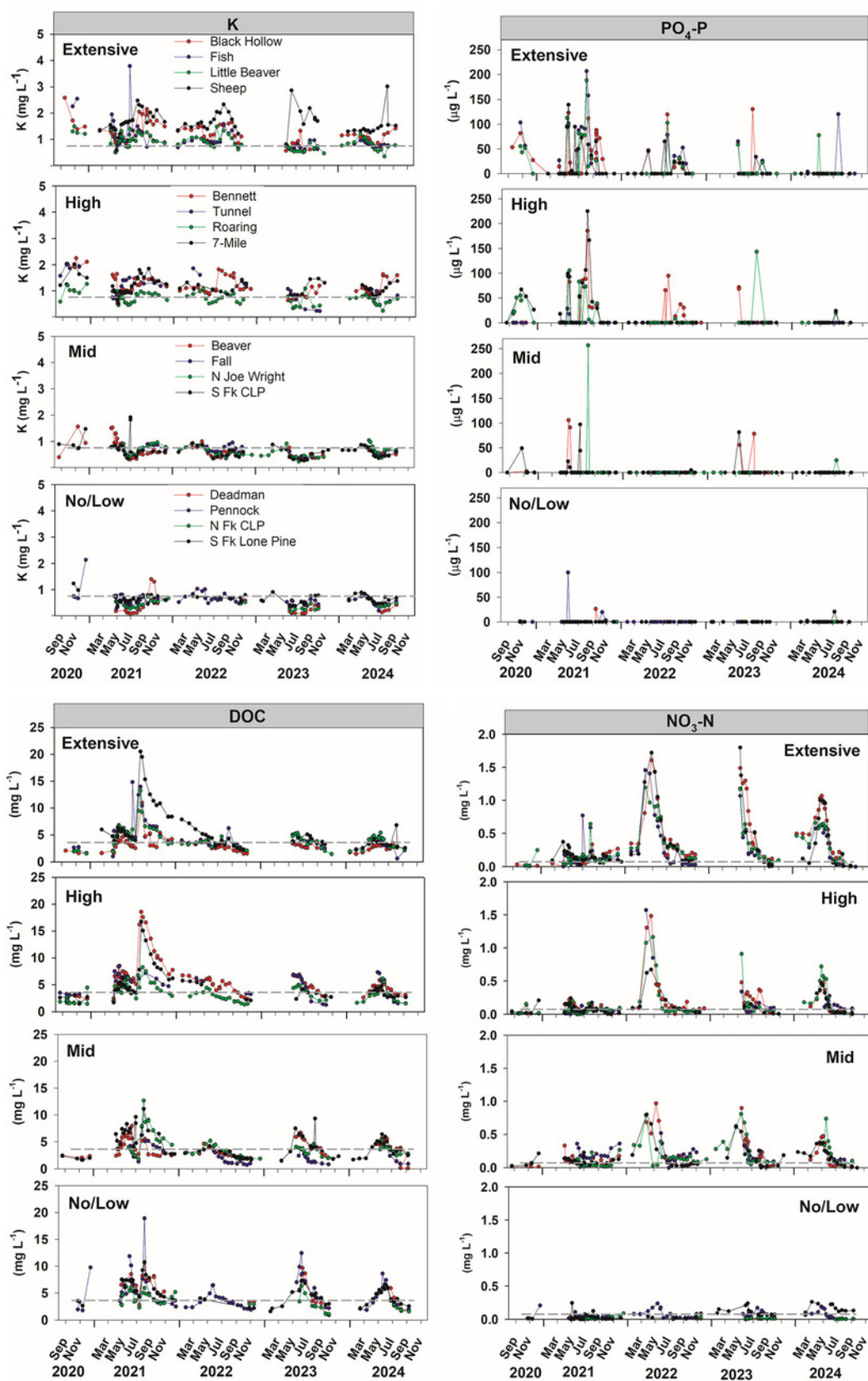
The residual ash and char remaining in June 2021 following the first post-fire snowmelt season had pH values 3 and 2.5 units higher than unburned O-horizon or mineral soil, respectively. With few exceptions, solute concentrations were higher in the char layer than in residual ash. Both NO₃-N and NH₄-N were twice as high in char compared to residual ash, and NH₄-N comprised 78% of the sum of inorganic N forms (DIN) in the two layers. Residual ash and char were leached into soils and mobilized by overland flow during summer storms in 2021 and were rare in subsequent years (C. Rhoades; personal observation).

In June 2021, pH and concentrations of all water-soluble constituents were significantly higher in mineral soil in burned forests compared to unburned sites, likely reflecting inputs leached from

fresh ash (Table 2). Soil pH was 1.2 units higher in burned mineral soils; many analytes were 1.5- to threefold higher (SC, ANC, K, Ca, Mg, Cl, TDN, DOC). The largest post-fire difference was for NH₄-N, which was 38 times higher in burned soils. In contrast, NO₃-N and PO₄-P were the only solutes with lower concentrations in burned soils.

Wildfire Extent and Severity Influences on Stream Water

In general, tributary solute concentrations and turbidity were closely related to wildfire extent and severity (Table 3). The two metrics (wildfire extent and high + moderate severity extent) explained half or more of the variability ($r^2 > 0.5$) in mean K, SO₄-S, PO₄-P, TDN, NO₃-N and turbidity aver-



◀**Figure 3.** Temporal solute concentration patterns following the Cameron Peak Fire in tributaries spanning a range of severe wildfire extent. The fire burned from August to December 2020. Instantaneous stream water samples were collected weekly (April to June) or biweekly (July to October) or monthly (November to March) during 2021 through 2024. A limited number of samples were collected in 2020 in areas where burning had ceased. Gray dashed line denotes the pre-fire average concentration measured in 5 of the study tributaries (2015–2020). Ortho-P was undetectable in pre-fire tributaries.

aged across seasons from 2021 through 2024. With few exceptions, wildfire extent was more closely related to variability in solute concentration (e.g., higher r^2) than the combined high + moderate severity metric. Both metrics increased solute maxima more, as indicated by higher slopes, than mean concentrations, though changes in goodness of fit were inconsistent. The two burn extent metrics explained more of the variability in the concentration of $\text{NO}_3\text{-N}$ than for any other solute (Table 3). Mean and maximum $\text{NO}_3\text{-N}$ concentrations increased by 0.3 and 1.6 mg L^{-1} , respectively across the range in burn extent and the concentration range for high + moderate severity extent was similar.

Temporal Responses

Stream water responses to the Cameron Peak Fire varied not only among chemical constituents and the extent of severe wildfire (Table 3), but also season (Figs. 3 and SI Figure 3) and years since the fire (SI Table 3). The solute-specific and temporal patterns corresponded to distinct transport pathways from burned landscapes to streams (that is, airborne ash, overland transport during rainstorms, and subsurface flow during snowmelt). Over four post-fire years, concentrations of most solutes returned to pre-fire conditions (SI Table 2), though some remained elevated and with the lasting effect on downstream water.

We observed increased solute concentrations in autumn 2020, while the fire was still burning and before the burn scar received significant rainfall, consistent with input of wind-borne ash directly into streams. The high K, $\text{PO}_4\text{-P}$ (Figure 3), $\text{SO}_4\text{-S}$, ANC and SC in stream water reflected enrichment of these solutes in fresh ash (Table 2). Increases were most evident in the Extensive severity class (SI Table 3), though they occurred in other classes also. In several of the study streams (Figure 3), these immediate post-fire K concentrations were

the highest measured at any time during the study. Due to the highly buffered nature of the stream water, inputs of alkaline ash had no immediate effect on stream water pH.

Stream $\text{PO}_4\text{-P}$ (Figure 3) and $\text{NH}_4\text{-N}$ (SI Figure 3) responded repeatedly to summer rain events (SI Table 1) with detectable concentration spikes compared to pre-fire below detection levels; spike concentration and frequency decreased with time since the fire. In 2021, $\text{PO}_4\text{-P}$ spiked between 11 and 17 times in the four Extensive catchments; each of them responded four or five times in 2022, and two or fewer times annually after that. Peak $\text{PO}_4\text{-P}$ decreased from 0.2 mg L^{-1} in 2021 to 0.1 mg L^{-1} from 2022 through 2024. There were numerous $\text{NH}_4\text{-N}$ peaks in 2021 and 2022, though the highest concentrations occurred in 2023 in the Extensive and High severity classes. In 2024, concentration spikes were rare for both solutes. In general, for $\text{PO}_4\text{-P}$, $\text{NH}_4\text{-N}$ and K the two higher extent classes differed from the Mid and No/Low classes (SI Table 3).

Stream DOC increased abruptly in July 2021 during a period of intense convective storms (Figure 3); peak concentrations in the Extensive and High severity catchments ($\sim 20 \text{ mg L}^{-1}$) were roughly twice pre-fire maxima (SI Table 2). The descent to pre-storm DOC levels continued through 2021 and into 2022. Typical seasonal DOC increases with spring snowmelt reemerged in 2022 and continued with few summer storm-related fluctuations through the rest of the study. Following the 2021 storm pulse and 2022 decline, post-fire DOC was similar or lower in the Extensive compared to the No/Low severity class (SI Table 3). Unlike the repeated storm-driven $\text{PO}_4\text{-P}$ and $\text{NH}_4\text{-N}$ spikes, the large peak and gradual recession of DOC and $\text{SO}_4\text{-S}$ (not shown) suggests the depletion of a finite pool of ash and charred organic material.

In contrast to the storm-driven patterns described above, post-fire responses of stream $\text{NO}_3\text{-N}$ and TDN (Figure 3 and SI Figure 3) tracked seasonal patterns typical of solutes that move along subsurface flowpaths in snowmelt-dominated watersheds (SI Figure 2). With the exception of a few storm-related spikes in 2021, the highest concentrations of both N forms occurred during spring snowmelt. Stream $\text{NO}_3\text{-N}$ increased dramatically in 2022 in the Mid, High and Extensive classes (Figure 3) after a one-year post-fire lag. Peak spring snowmelt concentrations were 1.7 and 1.8 $\text{mg NO}_3\text{-N L}^{-1}$ in 2022 and 2023 in Extensive catchments, roughly 10 times above pre-fire maxima (SI Table). In 2024, mean $\text{NO}_3\text{-N}$ in the Extensive class remained tenfold higher than the No/Low

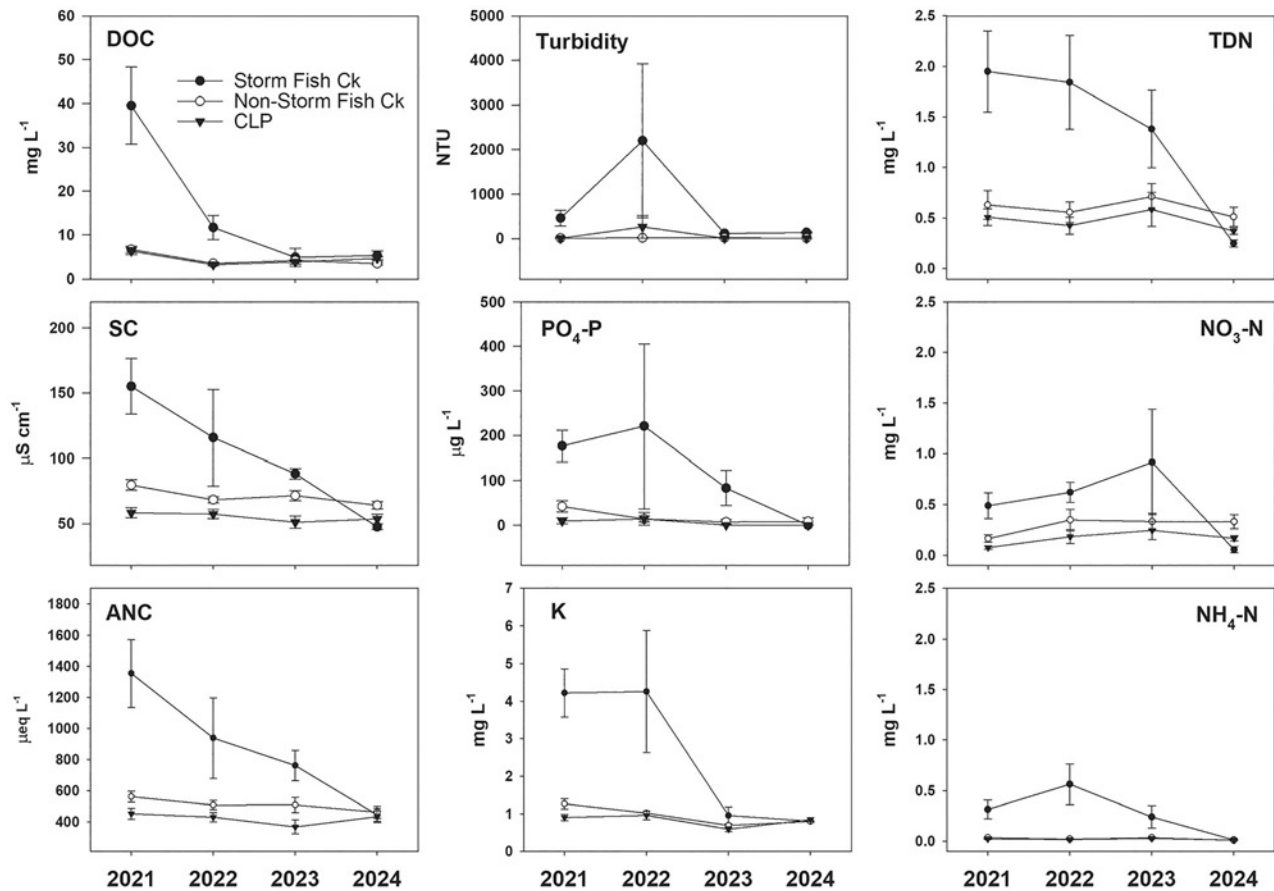


Figure 4. Solute concentrations in storm event and non-storm water in Fish Creek and the main stem of the Cache la Poudre River (CLP) after the Cameron Peak Fire. Storm data are means with SE of peak storm concentrations collected by an automatic sampler that was triggered at 50 NTU. Non-storm Fish Creek and CLP data are mean and SE from systematic samples collected during the summer storm season (July to September). Storm, non-storm and CLP data were compared using nonparametric Kruskal–Wallis analysis of variance.

class catchments, and the High and Mid classes were four times higher. Overall, post-fire TDN was twice as high in the Extensive catchments as in the No/Low catchments (SI Table 3). Like NO₃-N, mean TDN concentrations were highest in 2023 and remained elevated through 2024. Nitrate comprised 54% of TDN in Extensive catchments compared to 14% in the No/Low severity class catchments. Not only did NO₃-N differ between the Extensive and No/Low burn classes, but the two intermediate classes differed from the Extensive and No/Low end points during all post-fire years (SI Table 3).

Storm Responses

Concentrations of solutes that are readily mobilized in overland flow were much higher in storm water compared to either non-storm tributary water or the mainstem CLP (Figure 4 and SI Table 4). Tur-

bidity and TSS maxima were roughly 20 and 10 times higher, and NH₄-N, PO₄-P, K and DOC were 11, 7.5, 5 and 4 times higher in ISCO storm samples compared to systematic non-storm samples (SI Table 4). Storm water SC, ANC and Ca were twice that measured during non-storm conditions. In contrast, anions that tend to move along subsurface flowpaths (NO₃-N, Cl and SO₄-S) did not respond as strongly to rain storms.

Temporal post-fire storm patterns were most evident in Fish Creek, where peak storm concentrations were highest for most solutes the first two post-fire summers, then declined to non-storm tributary and CLP levels in 2023 or 2024 (Figure 4). Storm water DOC decreased by 75% between its peak in 2021 (mean: 40 mg L⁻¹ and max: 86 mg L⁻¹) and 2022 and then returned to non-storm levels. Both ANC and SC decreased uniformly from peaks in 2021 storms to non-storm tributary and CLP concentrations in 2024. In contrast, storm water

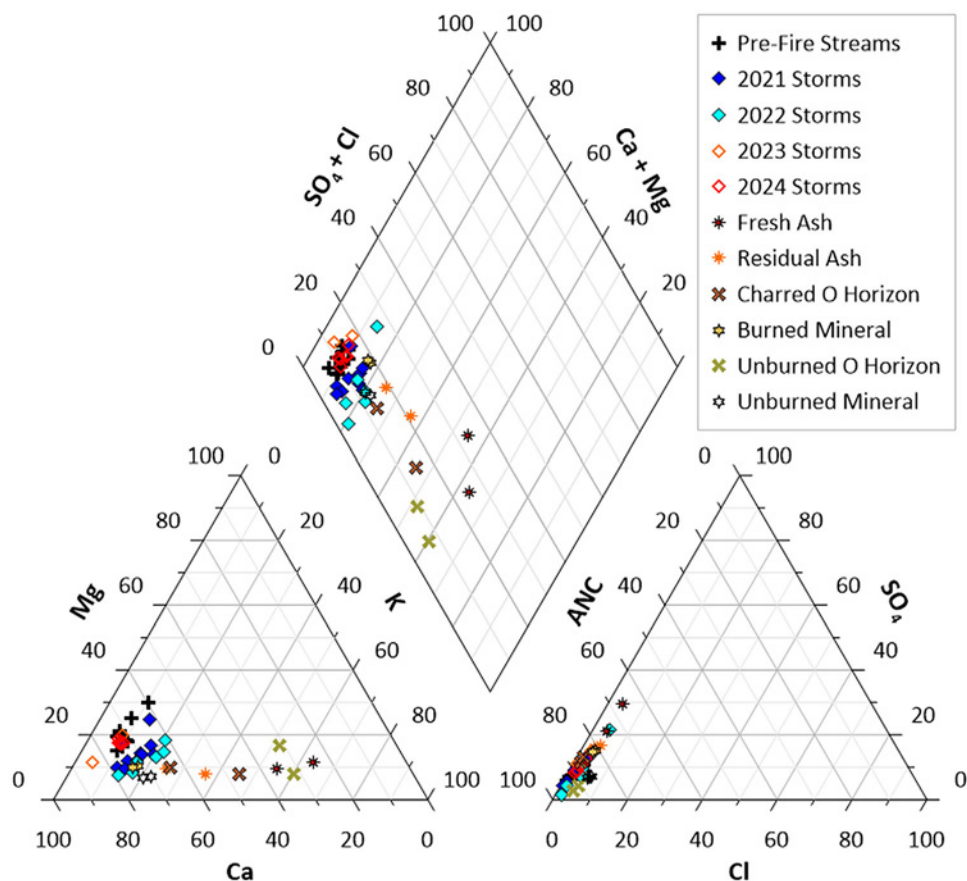


Figure 5. The proportion of dominant cations and anions in pre-fire stream water, post-fire storms, ash and soils within the Cameron Peak fire. Ternary graph axes show the proportion (%) that individual solutes represent of cation and anion sums. Pre-fire tributary data show spring and summer seasonal mean values for five streams during five years prior to the Cameron Peak Fire. Stormwater data are maximum concentrations from individual storms in Fish Creek. Ash, char and soil data are mean and maximum values ($n = 10$, Table 2).

$\text{PO}_4\text{-P}$, K , TDN , and $\text{NH}_4\text{-N}$ concentrations remained high through 2022 before declining. Peak storm water $\text{PO}_4\text{-P}$ and $\text{NH}_4\text{-N}$ concentrations exceeded 1 mg L^{-1} in 2022 for both solutes. Storm water turbidity (Figure 4) and TSS (not shown) also peaked in 2022, but unlike most other analytes they were relatively low in 2021. Nitrate was the only solute that continued to increase in storm water through 2023. Non-storm event concentrations of DOC , SC , K and $\text{PO}_4\text{-P}$ were highest in 2021, reflecting the lasting effect of ash mobilization during that year's high-intensity storms.

Graphical analysis highlighted similarities between ash and post-fire storm water chemistry (Figure 5). In fresh ash, K comprised more than half of the dominant cations, and its concentration was the highest among the cations measured (Table 2). Both K concentration and its proportion of dominant cations were lower in residual ash and char than fresh ash, though both attributes remained elevated compared to soils or surface water.

It is also notable that the proportions of K were similar between fresh ash and unburned O-horizon. In contrast, pre-fire stream chemistry was dominated by Ca and ANC ; these solutes represented 60–75% and 85–93% of dominant cations and anions, respectively.

Chemistry of the 2021 and 2022 storms reflected the elevated concentrations of K in ash (Table 2) and the shift in its importance relative to Ca and Mg in ash and char (Figure 5). For example, the proportion of K in 2022 storm water (14–22%) was twice that of pre-fire streams (7–11%). Similarly, SO_4 comprised a greater proportion of total anions in early storms; it represented up to 12% in pre-fire streams compared to 22% in 2022 storm water. The composition of storm water during 2023 and 2024 converged with pre-fire streams, showing the transient effect of wildfire ash.

Distinct pre- and post-fire relations between individual solutes provides additional evidence of the delivery of ash-related ions in storm water (SI

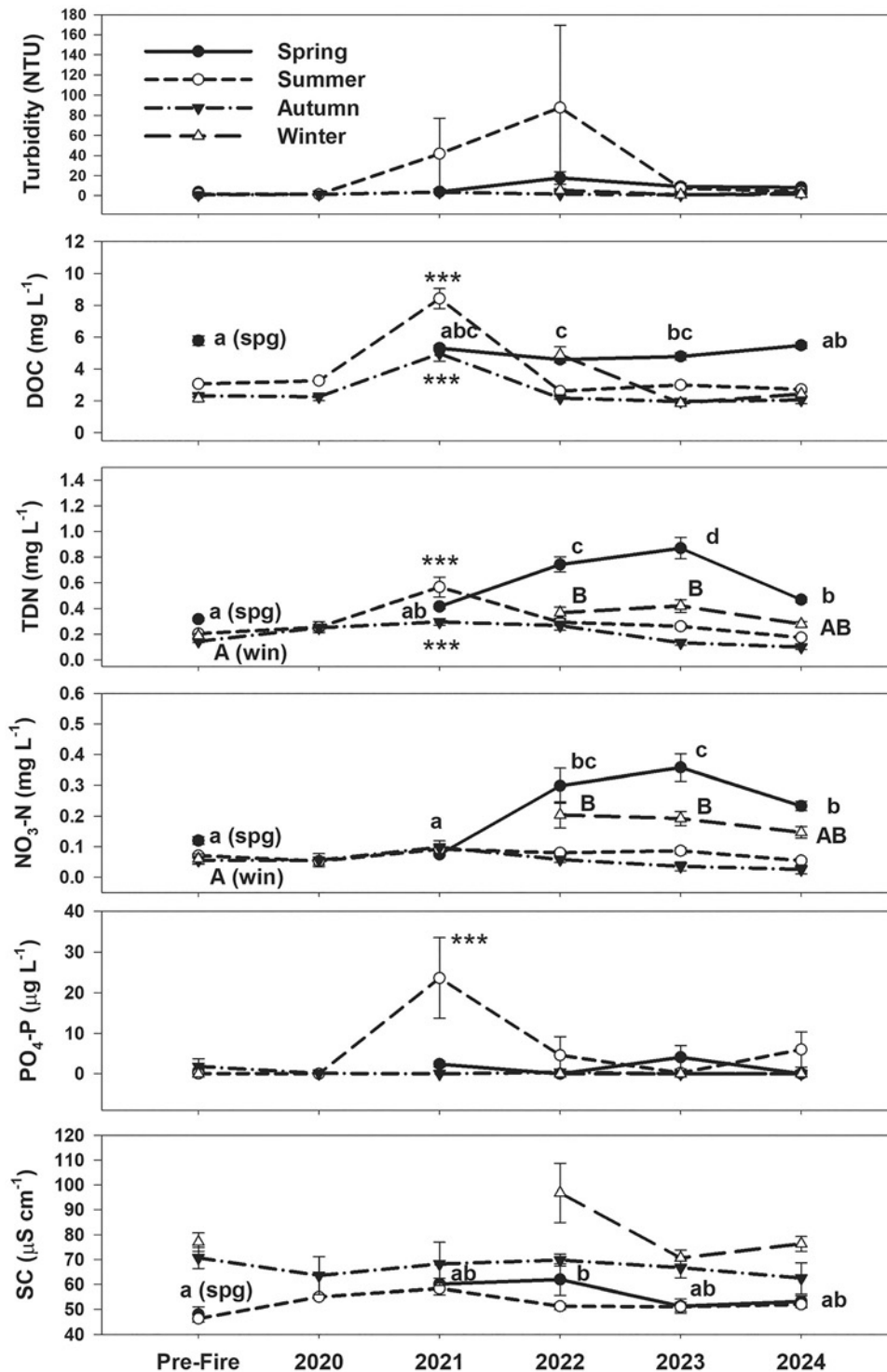


Figure 6. Solute concentrations in the Cache la Poudre River before and after the 2020 Cameron Peak fire. Data are seasonal means and SE for three sample locations spanning the fire scar. The pre-fire period extends from 2015 to 2020. In 2020 data include post-fire summer and autumn samples only. Seasons are differentiated as follows: Spring (April, May, June), Summer (July, August, September), Autumn (October, November, December), and Winter (January, February, March). Tributary and CLP data were compared using nonparametric Kruskal–Wallis analysis of variance. Letters show differences among years for seasonal mean data (small letters = Spring; capital letters = Winter) and *** denote significant differences relative to pre-fire seasonal mean concentrations. Note: samples were not collected during Winter 2021.

Figure 5). For example, though neither K nor $\text{PO}_4\text{-P}$ was well related to SC in pre-fire streams, both relations were strong (that is, higher r^2 and slope) in post-fire storm water. For K, the slope of the relationship with SC was 4 times higher in storms than during pre-fire conditions. In contrast, relations between SC with either Ca or ANC were fairly similar for pre-fire streams and post-fire storms. The ratio of K to Ca has been proposed as an indicator of wildfire ash inputs (Zeng and others 2024). Consistent with high K concentrations in ash (Table 2) and relative importance of K in ash, char and post-fire storm water (Figure 5), we found much higher K:Ca ratios in ash, char and unburned O-horizon compared to surface water or mineral soils (SI Figure 6). Like the relationship with SC (SI Figure 5), K concentrations were more closely related to Ca in 2021 and 2022 storm water than in pre-fire streams (SI Figure 4). The 2023 and 2024 storms had K concentrations equal to pre-fire streams and were not sensitive to changes in Ca. Overall, these patterns are consistent with rapid mobilization and depletion of ash by initial post-fire storms.

In addition to clear impacts on tributary stream water, the effects of the Cameron Peak Fire propagated downstream into the CLP. Changes in CLP water quality were first evident during the 2021 summer storm season (Figure 2); those storms increased turbidity, DOC, TDN and $\text{PO}_4\text{-P}$ (Figure 6) relative to pre-fire seasonal mean concentrations. That year, mean DOC concentrations in the CLP were more than double pre-fire means (8.4 vs. 3.1 mg L^{-1}), with summer season concentration maxima > 20 mg L^{-1} . Similarly, mean and maximum summer $\text{PO}_4\text{-P}$ concentrations increased from pre-fire levels (0.6 $\mu\text{g L}^{-1}$) to 24 and 256 $\mu\text{g L}^{-1}$, respectively. Summer storms in 2022 increased CLP turbidity to a greater extent than in 2021 though chemical responses were smaller. In contrast to summer storm-driven concentration spikes, $\text{NO}_3\text{-N}$ and TDN began increasing in the CLP during snowmelt in 2022 (Figure 6). Peak snowmelt concentrations in the CLP occurred in 2023, when $\text{NO}_3\text{-N}$ and TDN were about three times higher than pre-fire levels. Both solutes remained elevated through 2024.

DISCUSSION

In this study, we documented solute-specific temporal responses for four years following the Cameron Peak Fire (Figure 3 and SI Figure 3). The size of concentration increases related to the proportion of a catchment burned or burned at mod-

erate and high severity (Table 3). Summer storms, especially those the first two post-fire years, spiked tributary solute concentrations (Figs. 3 and 4), and those pulses propagated downstream to the CLP (Figure 6). Both immediate and storm-driven solute responses provide evidence of wildfire ash and charred organic matter transport from burned landscapes. Unlike the storm-driven patterns, $\text{NO}_3\text{-N}$ and TDN remained elevated throughout the study and tracked seasonal patterns typical of constituents transported along subsurface flow paths.

Immediate and Storm-Driven Ash Effects on Surface Water

We observed widespread increases in stream water concentrations of several constituents ($\text{PO}_4\text{-P}$, $\text{NH}_4\text{-N}$, K) that were enriched in wildfire ash and char while the fire was still burning (Figure 3 and SI Figure 3). Prior to significant rainfall or spring snowmelt, direct deposition and local redistribution by wind were likely modes of transport to surface water. Similarly, stream P and N increased fivefold to 60-fold within days of wildfires in Montana, USA, and remained elevated for days to weeks before declining to baseline concentrations (Spencer and Hauer 1991). In that study, laboratory assays indicated that ash, deposited directly into streams, was the P source, and that N was derived from smoke. Similarly, K and Ca concentrations in rain and stream water were elevated in western Canadian watersheds during years with abundant wildfires and smoke (Evans and others 2021). Smoke from fires in eastern Canada elevated P concentrations in stream water 700 km away in central New York, USA (Fernandez and others 2024), and fires in the northwestern US have influenced aerosol chemistry in Colorado (Creamer and others 2016). Given the relatively low concentration of $\text{NH}_4\text{-N}$ in fresh ash (Table 2), it seems likely that wildfire smoke was the source of elevated stream $\text{NH}_4\text{-N}$ we measured in autumn 2020.

'Black water' events following high-intensity convective storms are visible evidence of ash and char on post-fire surface water (SI Figure 4). Post-fire storms have been shown to have disproportionate effects on post-fire hydrology (Atwood and others 2023), sediment (Ryan and others 2024) and stream chemistry (Murphy and others 2018; Bush and others 2024). In 2021 and 2022, there were 27 days each year when turbidity in the CLP exceeded intake thresholds for drinking water treatment (100 NTU, Figure 2). The most turbid storm

sample recorded (21 July 2021) in Fish Creek also contained the highest concentrations of DOC (86 mg L^{-1}) and TDN (4.1 mg L^{-1}) measured during this study, and second highest for $\text{PO}_4\text{-P}$ (0.3 mg L^{-1}), $\text{NH}_4\text{-N}$ (1.0 mg L^{-1}) and $\text{NO}_3\text{-N}$ (1.2 mg L^{-1}). Those storms contained higher proportional concentrations of K and SO_4 and higher K:Ca ratios that differed from both later storms and pre-fire streams (Figure 6 and SI Figure 6). These patterns were consistent with rapid mobilization and depletion of K contained in ash derived from surface organic matter combustion (Zeng and others 2024). Similarly, stream solute concentrations were generally related to their concentrations in wildfire ash leachate shortly after a low–moderate severity wildfire, though relations were both discharge and site dependent (Richardson and others 2024).

Ash, char and eroded sediment are concerns for filtration, but high concentrations of C and nutrients also cause problems for water treatment operations (Emelko and others 2011; Hohner and others 2019). We observed a large pulse of DOC from the Extensive and High burn severity classes during the initial post-fire storm season followed by a gradual decline (Figure 3). Similarly, there were DOC pulses in excess of optimal treatment thresholds (5 mg L^{-1}) following convective storms after other Front Range fires (Writer and others 2012 and 2014; Akie and others 2024; Clow and others 2024). Drinking water treatment operators closely monitor the amount and composition of C supplied in intake water, which influence formation of disinfection by-products (DBPs) and other compounds that are potentially harmful to human health (Chow and other 2019; Hohner and others 2019). In addition to DOC, black water events following the Cameron Peak Fire contained elevated levels of benzene polycarboxylic acids (Thurman and others 2023; Chen and others 2022) and other DBP precursors (Uzun and others 2020; Bahureksa and others under review).

New advances in field-deployable, optical sensors have promise for tracking organic matter amount and chemical character and for targeting compounds created or altered during combustion (Akie and others 2024). Pyrogenic organic matter including char and ash contain compounds with lower molecular weight and higher aromaticity compared to unburned organic material (McKay and others 2020); these can be identified using optical fluorescence as a shift toward shorter wavelengths (Fischer and others 2023). However, sensors are currently limited by interference from suspended sediment and char-related turbidity that

co-occur during the storm events that mobilize pyrogenic organic matter (Penzel and others 2025).

Persistent Impacts and Modes of Transport

This study documented rapid changes in stream water the first four years after Colorado's largest wildfire. These short-term effects had significant impacts on water treatment and downstream water but may also have effects relevant to longer-term watershed recovery. For example, in addition to the ash inputs reported above, we documented increased $\text{PO}_4\text{-P}$ in one stream (Roaring Creek) that received aerial fire retardant during suppression operations. Ammonium phosphate-based slurry contains inorganic N and P in concentrations that are orders of magnitude above those found in forest soil and water (Gao and DeLuca 2021); operational applications delivered 337 kg N ha^{-1} and 94 kg P ha^{-1} (Bell and others 2005). Though the stream P concentrations we measured following slurry applications ($53 \text{ } \mu\text{g L}^{-1}$) abated quickly and were a fraction of those measured after post-fire storms (that is, $200\text{--}300 \text{ } \mu\text{g L}^{-1}$ Figs. 3 and 4), slurry increases N and P leaching (Pappa and others 2006, 2008; Gao and DeLuca 2021) and can have long-lasting effects on soil N and P, ectomycorrhizal colonization and plant community composition (Marshall and others 2016).

Increased stream $\text{NO}_3\text{-N}$ and TDN concentrations lagged a full year behind post-fire increases for other solutes and both of these N forms remained elevated throughout 2024 in extensively burned tributaries and the CLP (Figs. 3, SI 3; SI Table 3). Elevated stream nutrients are known to persist for years to decades following wildfires burning in various forest and watershed conditions (Rust and others 2018), continuing after post-fire overland flow and stream turbidity abate (Rhoades and others 2019a). Like other ecosystem disturbances (Vitousek and Reiners 1975), the increase in N export results from a combination of decreased plant N demand and higher soil N mineralization (Kurth and others 2014; Dove and others 2020). Though elevated post-fire soil N is relatively short-lived (that is, $< 5 \text{ yrs}$; Rhoades and others 2015; Jonas and others 2019), slow vegetation recovery can impact nutrient uptake and losses to stream water for much longer (Rust and others 2019). For example, sparse forest regrowth and low plant nutrient demand in catchments burned by the 2002 Hayman Fire (Chambers and others 2016) has been linked to elevated post-fire stream $\text{NO}_3\text{-N}$ lasting two decades (Rhea and others 2022).

Though the most dramatic effects of wildfires occur the first post-fire years, their long-term biogeochemical effects span repeated cycles of erosion, deposition, burial and remobilization of sediment, pyrogenic organic material and particulate forms of nutrients (Girona-García and others 2024; Peter-Contesse and others 2024). We observed a large pulse of C during the first storm season and spikes in $\text{PO}_4\text{-P}$ throughout the study period (Figure 3), though by 2024, storm effects on surface water were minimal (Figure 4). Downslope transport and integration of ash and char-derived nutrients and C into soil profiles occurs shortly after wildfire and determines whether it is stabilized or lost from burned watersheds (Masiello and Berhe 2020; Roebuck and others 2022). These processes also impact post-fire N and P cycling (Spencer and others 2003; Berhe and others 2018). The differences in soluble C, N, SO_4 , K and other cations in fresh ash compared to those remaining after the 2021 snowmelt season correspond to elemental enrichment of the underlying char and burned soils (Table 2). The long-term biogeochemical implications of these changes depend on whether burned soil layers are subsequently eroded. For example, integration of P-rich soils eroded from burned forests into stream bedload and subsequent remobilization during high stream flow enriched stream food webs for years (Emelko and others 2016).

Headwater Fires in a Changing World

Though the Cameron Peak Fire was the largest in Colorado history, several other fires burning in 2020 exceeded the previous state record fire. The extent of wildfire has increased dramatically in recent decades in the western USA (Parks and Abatzoglou 2020; Iglesias and others 2022) and more large, severe fires are expected. The Cameron Peak burn scar combined with the adjacent 2012 High Park Fire has altered more than 60% of the headwater forests of the Cache la Poudre watershed (Figure 1). For land managers, residents and water utilities on the Colorado Front Range and across western North America, these changes represent what “Living with More Wildfire” (sensu Schoennagel and others 2017; Balch and Williams 2024) may mean for headwater forests.

Wildfires do not occur in isolation and their impacts, combined with co-occurring climate and land-use changes, aggravate pre-fire water supply, storage, and delivery concerns (Nunes and others 2018; Belongia and others 2023). Elevated post-fire stream N exacerbates widespread trends in increasing atmospheric N deposition that threaten

the capacity of watersheds to retain N inputs with potential consequences for aquatic ecosystem health, harmful algal blooms and drinking water treatment (Emelko and others 2011; Stoddard and others 2016). For example, severe wildfire in southern California watersheds in areas with chronic N enrichment from air pollution, resulted in stream N concentrations that exceeded drinking water standards (Riggan and others 1994). The Colorado Front Range receives increasing amounts of N from adjacent urban, agricultural and oil and gas development areas (Repert and others 2025), which may contribute to persistent post-fire stream N responses in the region (Rhoades and others 2019a). Further, constituents delivered by wildfire ash, smoke and hillslope flowpaths (that is, N, P, K) have the potential to shift nutrient limitations in aquatic ecosystems (Butler and others 2018; Rhea and others 2021; Scordo and others 2021). There is need for more complete understanding of the solute-specific discharge relations that couple ash to stream water (Crandall and others 2021; Richardson and others 2024) and that regulate solute transport via surface and subsurface flowpaths (Murphy and others 2018; Bush and others 2024). Though remote sensing analyses found no recent evidence of widespread eutrophication in high-elevation lakes in the intermountain West (Sillen and others 2024), the post-fire responses we report coupled with growing concerns about nutrient enrichment in local reservoirs (Heath and Thorp 2023) justify further evaluation. The influence of wildfires coupled with preexisting watershed stresses remain poorly understood (Rhoades and others 2019b) and require greater process-based understanding of how wildfires alter the biogeochemistry of high-elevation reservoirs and influence downstream, sometimes distant, land-use activities (Barnard and others 2023; Nichols and others 2024).

Implications for Managing Watersheds to Accommodate Future Fires

Though there is growing awareness of the need to live with more fire (Schoennagel and others 2017; Balch and Williams 2024), there is little agreement about the best approaches for mitigating wildfire risks or post-fire responses. On US Forest Service land, immediate post-fire efforts survey soil burn severity and prioritize treatments in areas with high erosion potential (BAER 2023). The impacts of these management efforts on the nutrient retention and cycling processes that regulate stream water quality at catchment scales remain poorly under-

stood (Rhoades and others 2025). Revegetation has potential to enhance nutrient retention in burned watersheds, especially where it occurs in biogeochemically active near-stream locations (Rhea and others 2022). However, reforestation is currently constrained by low nursery production and planting capacity (Dobrowski and others 2024), and most current projects prioritize replanting upland forests. There is growing interest in post-fire projects that use wooden structures to mimic interactions between beavers (*Castor canadensis*), hydrology, and vegetation to add complexity to stream channels and floodplains (Pollock and others 2014). These approaches redistribute stream-flow and enhance sediment and particulate organic material storage (Dunn and others 2024), but they also have potential to increase C, N, and P retention. Though the implications of these practices on post-fire watershed conditions are unknown, their potential benefits for native biodiversity, habitat, climate resilience and C sequestration justify evaluation.

Every ecosystem disturbance is unique. The landscape and ecosystem complexity encompassed by large wildfires contribute to variable spatial patterns of fire behavior and severity. However, both our findings from Colorado's largest wildfire and syntheses from wildfires across the western USA (Hallema and others 2017; Rust and others 2018) demonstrate that severe wildfires can influence surface water supply and quality for years to decades, well beyond the time span of funding typically available for post-fire rehabilitation and monitoring. Lessons from the Cameron Peak Fire advance understanding of solute-specific, temporal post-fire impacts to stream water. These findings can help guide expectations about post-fire response and recovery and prioritize areas that may benefit from post-fire restoration. As a whole, this information should assist land managers, residents and water utilities to better understand what larger extents of severe wildfire could mean for sustained clean water supply from headwater forests.

ACKNOWLEDGEMENTS

Many thanks to three anonymous reviewers, Dr Sujay Kaushal and Dr Susan Miller for comments that greatly improved this manuscript. We are extremely grateful to Ashlynn Piwowarczyk, Isabel McPherson and numerous technicians for assistance in the field and laboratory. Thanks to the Coalition for the Poudre River watershed for coordinating citizen-based stream monitoring that contributed to the pre-fire stream samples we

analyzed in this project. We thank landowners impacted by the fire who graciously permitted access to their land, especially Maya Dauro and Dan Bond. This work is dedicated to the memory of the CLP residents who lost their lives during the 2021 Black Hollow flood following the Cameron Peak Fire. Funding for this work was provided by the US Forest Service, Rocky Mountain Research Station, the Bipartisan Infrastructure Law (H.R. 3684), the Arapaho-Roosevelt National Forest, Northern Water and the cities of Fort Collins, Greeley and Thornton.

FUNDING

The findings and conclusions in the publication are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy. This research was supported in part by the U.S. Department of Agriculture, Forest Service.

DATA AVAILABILITY

Data are available at: Rhoades, Charles C.; Fegel, Timothy S. 2025. Cameron Peak fire stream water chemistry. Fort Collins, CO: Forest Service Research Data Archive. <https://doi.org/10.2737/RDS-2025-0038>

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