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Assessing the effects of woody mulch on post-fire soil and stream nitrogen at experimental and operational scales

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A B S T R A C T

Severe wildfires often increase nitrogen (N) losses from burned forests which can impact downstream water quality, water treatability, and aquatic habitat. Woody mulch is commonly applied to mitigate post-fire soil erosion and enhance revegetation, but it is also a source of labile carbon (C) that can stimulate microbial immobilization and limit N release to soil and streams. The objective of our study was to evaluate whether woody mulch application could reduce N losses from soils and export from watersheds affected by the 2020 Cameron Peak fire in Northern Colorado, USA. Our assessment evaluated the potential for mulch to influence N cycling at various spatial scales including laboratory trials using mulched soil columns, field measurements on aerially mulched hillslopes, and replicate mulched and unmulched catchments. As expected after severe wildfire, we found elevated levels of various forms of N in burned hillslope soils and stream water in extensively burned catchments. Woody mulch released high concentrations of soluble C into soils and decreased nitrate leaching both from soil columns and burned hillslopes. However, there was no detectable effect of mulch on stream water N or C, likely due to low mulch coverage and high landscape complexity at the catchment scale. Though we observed that mulch has the potential to reduce post-fire N losses, soil N remained elevated compared to unburned soils. Logistical constraints on aerial mulching limited mulch application rates in our study. Uncertainties about where mulch applications are most effective constrain the utility of this treatment to alter post-fire water quality at magnitudes relevant to downstream users. Land managers would benefit from a better understanding of how to match the positive outcomes of post-fire mulching to the most biogeochemically sensitive locations within burned watersheds.

1. Introduction

In western North America, the frequency, severity, and size of wildfires have increased in recent decades (Dennison et al., 2014; Weber and Yadav, 2020; Cunningham et al., 2024). These changes relate to rising air temperature (Jones et al., 2022) and earlier snowmelt (Westerling, 2016) among other factors and are expected to continue into the future. Combustion of forest biomass and organic surface layers and post-fire reductions in plant nutrient and water demand are known to elevate soil nutrient content (Certini, 2005) and losses to streams via surface and subsurface flow paths (Murphy et al., 2006; Paul et al., 2022). Though post-fire soil nutrient losses are most notable the first few years after a fire (Rust et al., 2018), wildfire impacts on soil and stream nitrogen (N) can persist for many years (Kurth et al., 2014; Rust et al., 2019; Dove et al., 2020). There is concern that the more extreme wildfire behavior expected in the future will exacerbate nutrient and carbon (C) losses from forest soils and watersheds (Hohner et al., 2019) and may justify treatments aimed at optimizing the biogeochemical processes that reverse post-fire impacts on soil N and stream water quality.

Woody mulch is commonly applied to cover exposed mineral soil and limit post-fire erosion and water quality impairment (Robichaud et al., 2013; Prats et al., 2016). The treatment has gained favor in western North America, where utilization of abundant local sources of woody mulch are compatible with fuel reduction management objectives. As opposed to agricultural straw, another common erosion treatment (Girona-García et al., 2021), wood mulch tends to persist longer and have fewer risks of introducing native plant seed. Wood mulch can also enhance plant recovery (Jonas et al., 2019) and moderate soil N cycling after wildfire (Rhoades et al., 2017). Labile C released from mulch stimulates microbial metabolism and demand for soil N (Uwituze et al.,

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2023). This immobilization process incorporates soil N into microbial biomass, where it is less likely to be leached or transported to streams. Prior studies conducted at plot and hillslope scales show that woody mulch can reduce inorganic N both in unburned (Homyak et al., 2008; Rhoades et al., 2012) and burned soils (Rhoades et al., 2015). However, few studies have evaluated the treatment at landscape or catchment scales to determine whether woody mulch has the potential to have measurable impacts on post-fire soil N losses and stream water export.

Following the 2020 Cameron Peak fire, the largest wildfire in Colorado history, woody mulch was applied to more than 40 km^2 of the burn scar (CPRW, 2022), at a cost of $24 million US. Yet the land managers, water utilities and water regulators who directed and funded the work lack information about whether post-fire mulching has measurable consequences on stream water N and C at operational scales. To address this knowledge gap, we evaluated the potential for mulch to alter N losses at three spatial scales, including: 1) controlled laboratory column studies, 2) operationally mulched hillslopes and 3) catchments. As has been shown elsewhere, we expected mulching to reduce nitrate (NO_3-N) leaching at small, experimental scales, but we expected that detection of mulch impacts would decrease at larger spatial scales. This study will help elucidate the practicality of post-fire mulching treatments for influencing water quality at scales relevant to downstream users.

2. Methods

2.1. Site description

This research was conducted in the 2020 Cameron Peak fire scar on the Arapaho-Roosevelt National Forest in northern Colorado (Fig. 1A; Richardson, 2024). In conjunction with local US Forest Service staff and the water utilities, hydrologic consultants and watershed stakeholder organizations overseeing mulching operations, we selected six adjoining catchments in the Bennett Creek watershed with relatively uniform and high wildfire severity. Moderate + high severity wildfires, those that combust nearly all above-ground vegetation and organic soil layers, expose mineral soil to post-fire erosion and changes in soil productivity (Parsons et al., 2010); such conditions ranged from 80 % to 95 % within the study catchments (BAER, 2023) (Fig. 1B). For comparison, the combination of moderate + high severity wildfire that occurred in the Bennett Creek watershed as a whole and the entire Cameron Peak fire were 38 and 37 %, respectively.

Prior to the fire, the study catchments supported a dry, mixed-conifer forest comprised of lodgepole pine (*Pinus contorta*), Douglas fir (*Pseudotsuga menziesii*), and ponderosa pine (*Pinus ponderosa*) (Rodman, et al., 2022). Soils are gravelly-cobbly, sandy loam Inceptisols derived from colluvium and residuum weathered from granitic, gneiss, and schist parent material (Shaver et al., 1988). Soil profiles extend to 50 cm (Web Soil Survey, 2023). The study catchments range from 2342 to 2779 m elevation and receive 470 mm of precipitation annually (PRISM Climate

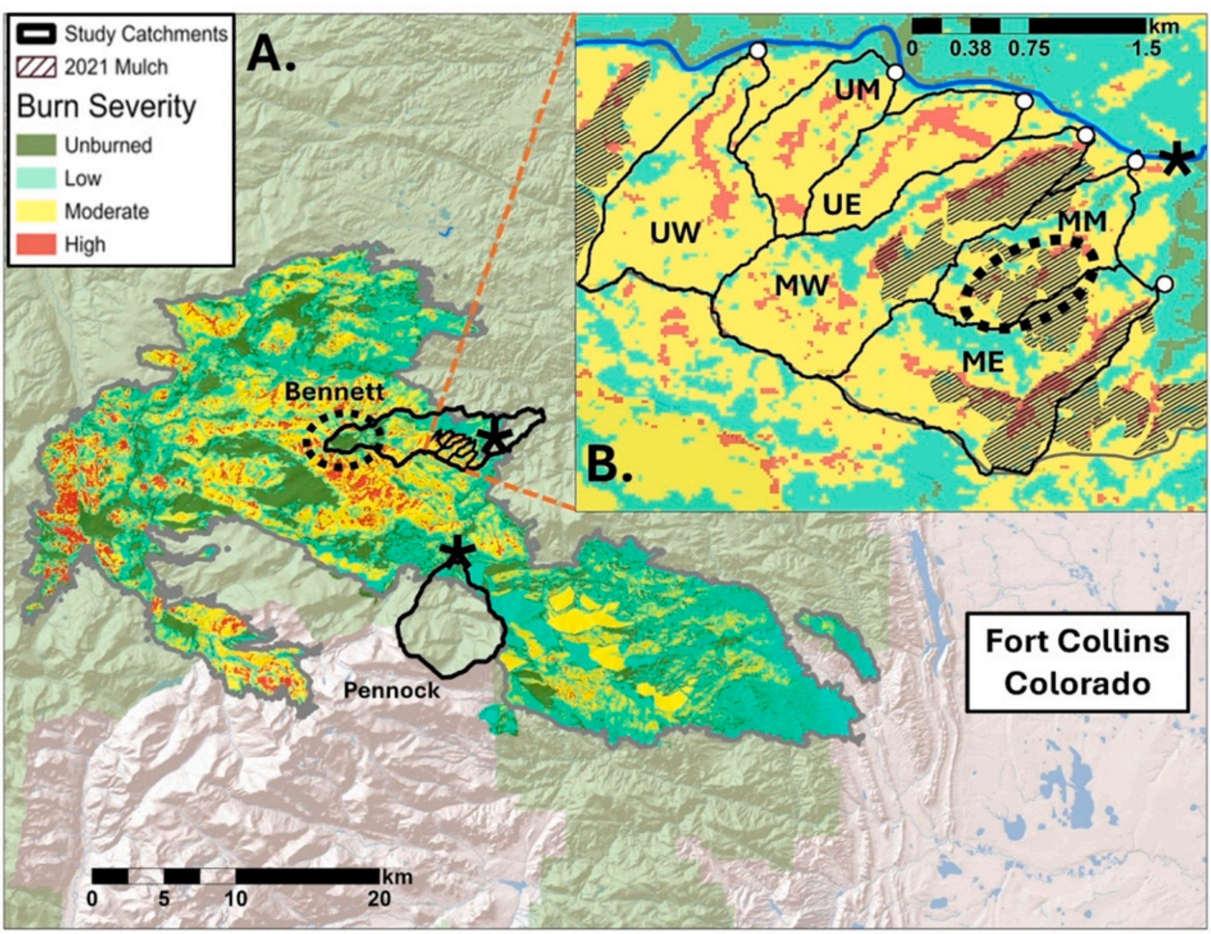

Fig. 1. A) The 2020 Cameron Peak fire with burn severity and the Bennett and Pennock Creek watersheds outlined (asterisks denote sample locations). The unburned reference forest hillslopes were located within the dashed circle. B) The Bennett Creek study catchments (black outlines), with mulch application areas (dark gray shaded) and stream sampling locations (denoted by white dots). The remulched hillslopes were located within the dashed circle. The Cameron Peak fire burned 70 % of the Bennett Creek watershed with 38 % at high + moderate severity and 16 % of Pennock Creek at low severity.

Group, 2022) as snow and rain, including high-intensity summer storms.

2.2. Evaluating mulch effects at three spatial scales

We assessed mulch effects on N cycling and loss at three nested scales (soil column, hillslope and catchment), detailed separately below. Catchment-scale mulching and the soil column study were both conducted in 2021, one year after the fire. Supplemental mulching and the hillslope scale trial occurred the following year. The laboratory-based soil column study characterizes NO_3-N and C leaching during four consecutive simulated rain events, comparing standard and augmented mulch depths. The hillslope-scale trial evaluated woody mulch applications on soil N movement during dry/summer and wet/winter conditions. Stream water analysis aggregates mulch effects across the catchment scale to examine potential impacts at the scale of greatest interest to downstream users. In combination, these interrelated scales of inquiry help advance understanding of benefits and limitations of mulching on soil and stream N in post-fire environments.

The fire burned until November 2020 and non-fire-suppression activities were prohibited in the burn scar until 2021. Though the one-year delay in starting mulch operations was not ideal, because of the challenges of prioritizing and delineating mulch areas, acquiring helicopter mulch contractors, and harvesting timber and creating woody mulch, this timing was unsurprising. Before detailing methodological approaches at the various spatial scales, we describe our analysis of wildfire effects on soil and watershed biogeochemistry in the study area and give an overview of the catchment- and hillslope-scale aerial mulching operations.

2.3. Wildfire effects on soil and stream biogeochemistry

To provide post-fire context for the mulching study, we compared soil and stream N and C for burned and unburned hillslopes and catchments (Fig. 1A). First, to characterize the influence of wildfire on soil N and C stocks, net N transformations and leaching potential we sampled burned, but unmulched hillslopes and unburned hillslopes (2 ×2 m plots; n = 12) in the Bennett Creek watershed (Fig. 1A and B). Two mineral soil cores were collected with a 5-cm diameter bulb corer, split into 0–5 and 5–15 cm depths and composited for each plot. Rocks and roots were removed by hand, and samples were stored at 4 °C until extraction (< 7 days) or other analysis. Inorganic N (NO_3-N and NH_4-N) was extracted from 20 g subsamples of mineral soil in 100 mL of 2 M KCl. Solutions were shaken for 60 minutes, extracts were passed through 1.2 µm glass microfiber filters and then analyzed for NO_3-N and NH_4-N using colorimetric spectrophotometry on a flow injection analyzer (FIA8000 + Lachat Company, Loveland, CO, USA). The detection limit for both N forms was 0.05 mg L^{-1}. Instrument values were corrected with field and laboratory blanks.

To assess inorganic soil N production, a second 20 g subsample of mineral soils was wetted to 60 % of field capacity and incubated at 20 °C for 21 days (Hart et al., 1994). Samples were loosely capped and rewetted periodically to maintain uniform soil moisture. At the end of the incubation, soil samples were extracted and analyzed for NO_3-N and NH_4-N as described above. Net transformations were calculated as follows: net mineralization = $(NO_3\text{-N} + NH_4\text{-N})t_{21\ d} - (NO_3\text{-N} + NH_4\text{-N})t_0$; net nitrification = $(NO_3\text{-N})t_{21\ d}$ – $(NO_3\text{-N})t_0$. A 10 g subsample was oven-dried at 105 °C for 24 h to determine gravimetric soil water content and used to convert N concentrations to a dry mass basis. Air-dried mineral soil subsamples were passed through a 2-mm mesh sieve, ground to a fine powder, and analyzed for total N and C by dry combustion using an elemental analyzer (CN802 Velp Scientifica, Deer Park, NY, USA).

We compared stream water in the main stem of Bennett Creek and a nearby, largely unburned watershed (Pennock Creek; Fig. 1A). Stream water was sampled weekly (April to August) or biweekly (September to October) throughout 2022. Samples were collected in HDPE plastic bottles, stored cold and filtered through 0.7 µm pore-size glass fiber filters (Millipore Corp, Burlington, MA). 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} Shimazdu Corporation, Columbia, MD). Detection limits for DOC and TDN were 0.04 and 0.01 mg L^{-1}, respectively. Stream NO_3-N and NH_4-N concentrations were determined by ion chromatography using electrical conductivity detection on AS19A anion-exchange and CS12A cation-exchange columns (Thermo Fisher, Waltham, MA). Detection limits were 0.01 mg L^{-1} for both N forms. Turbidity was measured using the nephelometric method (APHA, 1998; HF Scientific, Inc. Micro 100 Turbidimeter).

2.4. Aerial mulching

Approximately 340 ha of the Bennett Creek watershed was aerially mulched by helicopters in July and August 2021 using wood from locally harvested trees. Aerial mulch operations were conducted by private contractors, coordinated by consulting watershed managers working with local US Forest Service staff. Mulch was comprised of wood shred (10–20 cm in length, <2.5 cm in diameter) with minimal fine particles (JW Associates, pers. comm.). Mulch was applied to three of the catchments, and three adjacent catchments were left unmulched (Fig. 1B). To increase mulch persistence and impacts, steep, rocky sites and adequately revegetated sites were avoided. The portions of the catchments that were selected had slopes between 20 % and 60 % with minimal exposed rock and low post-fire vegetation regrowth. Overall, the delineated areas comprised 29 % of the three treated catchments. Summer rainstorms that occurred during July and August 2021 as mulch operations were underway generated soil erosion in the study area and throughout the Cameron Peak fire scar and impacted downstream water quality (Rhoades et al., in review).

Prior research has determined that 70 % mulch cover is required to control post-fire erosion (Robichaud et al., 2013; Girona-García et al., 2021), and this was the threshold designated for the study catchments and across the Cameron Peak fire (JW Associates, pers. comm.). We surveyed the designated treatment areas within 45 days of aerial operations and quantified mulch, bare soil, rock, vegetation, and coarse wood cover using the point intercept approach in 50 cm^2 gridded quadrats. Sample quadrats (n = 92) were distributed along transects that were evenly spaced within designated mulch areas in the study catchments. Overall, mulch cover averaged 22 % (maximum: 84 %) and reached the 70 % cover threshold in 8 % of the quadrats. Combining the extent of designated mulch areas in the study catchments (29 %) with the average measured mulch cover (22 %), we estimated that mulch cover was 6 % across the three study catchments.

To compensate for the low mulch cover applied during 2021 additional mulch was applied in July 2022 to allow hillslope-scale comparisons in a subset of the study catchments. The hillslope study areas were located where 2021 mulch cover was extremely low (< 6 %). Remulching created the following treatments on three hillslope replicates: no mulch (0 +), one additional aerial drop (1 +), or two additional aerial drops (2 +). The need to remulch was not part of the original study plan but provided the opportunity to evaluate mulch at a hillslope scale.

We established four 2 × 2 m plots in each burned hillslope treatment area (n = 12 plots per treatment) and a similar number on three nearby unburned hillslopes. The unburned hillslopes were < 3 km away from the burned hillslope study sites, and had similar pre-fire tree species composition, aspect and elevation. Mulch cover averaged 6, 36 and 40 % on the + 0, + 1 and + 2 treatment hillslopes. Overall, for both the + 1 and + 2 remulch levels, 6 % of the sample quadrats reached the 70 % cover threshold. Mulch depth was similar on the two remulch treatments and averaged 0.92 cm. Based on average mulch bulk density (0.25 g cm^{-3}; n = 5) and cover, we estimated that 5 Mg ha^{-1} was applied to the remulched hillslopes.

2.5. Soil columns: mulch effects on N leaching during simulated rainstorms

We used soil columns and simulated rainfall events to evaluate whether mulching influenced N leaching from burned soils. Soil columns contained mineral soil collected from the 0–5 cm depth of burned hillslopes that was covered with 0, 1, or 5 cm thick layers of woody mulch. Soil for the column study was collected in July 2022 from unmulched hillslope areas described above. The 1-cm mulch treatment approximated the average depth measured on mulched hillslopes (0.92 cm). The treatments added mulch equivalent to 0, 14 and 70 Mg ha^{-1} (n = 10 replicates per treatment). Mulch used in the column study was the same material described above.

To create the soil columns, mineral soil was first passed through a 2-mm mesh sieve, then packed into plastic columns (5 cm diameter, 100 mL volume, bulk density = 0.88 g cm^3; n = 10). Columns were seated on funnels containing 1.2-µm glass microfiber filters. Mulch was passed through a 3.4-mm mesh sieve, then loosely packed (bulk density = 0.13 g cm^3; n = 10) on the soil surface. To isolate the concentrations of N and C released from mulch or the inputs to the soil columns, we also created columns containing mulch only.

We conducted four consecutive rainfall events each consisting of 25 mL of DI water (equivalent to 20 mm of precipitation) to approximate the average number of summer storms and rainfall inputs in the study area (NOAA, 2024). Rainfall was repeated and leachate samples collected on weekly intervals. Soil and mulch only columns were loosely covered to reduce drying and maintained at 20°C between events. Leachate concentrations of DOC, TDN, NO_3-N, and NH_4-N and total C and N content in sieved mulch were analyzed as described above.

2.6. Hillslopes: mulch impacts on soil N availability and moisture

We evaluated the effects of wildfire and woody mulch treatments on soil N within the remulched hillslope plots that received + 0, + 1 and + 2 supplemental mulch applications. We measured plant-available soil nitrate (NO_3-N) and ammonium (NH_4-N) and potential leaching using ion exchange resin (IER) bags (Binkley and Matson, 1983). The bags contained a 1:1 mixture of cation (Sybron Ionic C-249, Type 1 Strong Acid, Na^+ form, Gel Type) and anion (Sybron Ionic ASB-1P Type 1 Strong Base OH^- form, Gel Type) exchange resin beads that adsorb NO_3-N and NH_4-N moving in soil water. Three IER bags were buried 5–10 cm deep below the soil surface in each burned and unburned hillslope plot (n = 12 per plot and treatment) to sample leachate moving within the upper 10 cm of mineral soil. Burned sites contained no organic horizon, whereas the unburned reference plots had 7–10 cm thick organic horizons. IER bags were deployed in July and October 2022 to collect inorganic N mobilized by summer rain events and spring snowmelt, respectively. The IER bags were collected at the end of each deployment period and stored at 4 °C until processing within 72 h. IER resins were removed from bags, rinsed with DI water and extracted with 100 mL of 2 M KCl and analyzed for IER-NO_3-N, and IER-NH_4-N, as above.

Mulching typically influences soil moisture and in turn soil N cycling and losses. Thus, volumetric soil water content (VMC) was measured in the remulched and unburned hillslope plots areas following the July 2022 remulching. Sampling occurred weekly during August, and monthly through November 2022 and in May 2023 using a hand-held time domain reflectometry probe (CD 620, HydroSense Campbell Scientific, Logan, UT). On each sample date, replicate measurements of VMC were recorded in the upper 10 cm of mineral soil beneath mulch or surface organic layers (n = 6 per plot).

2.7. Catchments: consequences of operational-scale mulching on stream N and C

We analyzed stream water quality in three mulched and two unmulched study catchments (Fig. 1B). Streamflow ceased in mid-May in a third unmulched catchment, so it was not included in these analyses. Stream water was sampled weekly (April to August) and biweekly (September to October) throughout 2022 and analyzed as described above. Stream water N and C concentrations were sampled and analyzed as described above for Bennett and Pennock Creeks.

In addition to comparisons of mulched and unmulched catchments, we characterized and examined how topographic and geomorphic features, vegetation recovery and fire severity of catchments influenced stream N and C concentrations. The number of channel heads is an indicator of the extent of surface erosion in each catchment and was determined using drone imagery. Erosion pathways were identified using the elevation difference between two subsequent drone images combined with visual interpretation of drone aerial photos. The top of each erosion pathway was counted as a channel head. The fraction of each catchment comprised of valley bottoms is an indicator of potential riparian areas that may affect stream N and C; this was determined using the geomorphon approach using Whitebox tools (Jasiewicz and Stepinski, 2013). Post-fire vegetation recovery was estimated using the normalized differenced vegetation index (NDVI) from Landsat 8 imagery collected in August 2022. Burn severity was classified using a differenced normalized burn ratio (dNBR) from pre- and post-fire satellite images (BAER, 2023).

2.8. Statistical analyses

We evaluated whether mulching had significant impacts on N and C in soil, leachate, and stream water measured at the various spatial scales. For the soil column study, we evaluated the general effect of mulch treatment on leachate C and N rainfall events using a mixed model analysis of variance with treatment and rain event as fixed and random effects, respectively followed by one-way analysis of variance to evaluate individual rain events (IBM SPSS Inc., Armonk, NY, V. 29). At the hillslope scale, we tested the effect of mulch treatment on IER-N within seasons and VMC within months using a one-way analysis of variance. Stream C and N concentrations in the study catchments during 2022 were compared using one-way analysis of variance. We also used least-squares regression to evaluate the relation between catchment geomorphic conditions and seasonal stream chemistry. We tested assumptions of normality and equal variance (Levene's test, Keyes and Levy, 1997) and log-transformed values as needed, to correct for unequal variances. Treatment effects were considered significant at $p < 0.05$. Where significant treatment effects occurred post-hoc means comparisons were made with Tukey's Bonferroni adjusted p-values.

3. Results

3.1. Watershed and hillslope effects of the fire on N and C

In 2022, the second summer after the fire, Bennett Creek streamwater N, C and turbidity concentrations were elevated relative to Pennock Creek, a nearby watershed that experienced minimal burning (84 % unburned); nearly all burned at low severity (Fig. 1A and 2). Nitrate-N (NO_3-N) and total dissolved N (TDN) both peaked during spring snowmelt in Bennett Creek and then subsided through summer and fall. Nitrate-N comprised > 93 % of all dissolved N in streamwater during spring snowmelt season in Bennett Creek. Conversely, in Pennock Creek there was a small snowmelt increase in NO_3-N; this suggests that stream N was dominated by organic forms of N in the mostly unburned catchment. A spring peak and subsequent decline in DOC lagged behind the N response in Pennock Creek. In Bennett Creek, stream DOC declined steadily throughout 2022. Summer storms (May-September) triggered

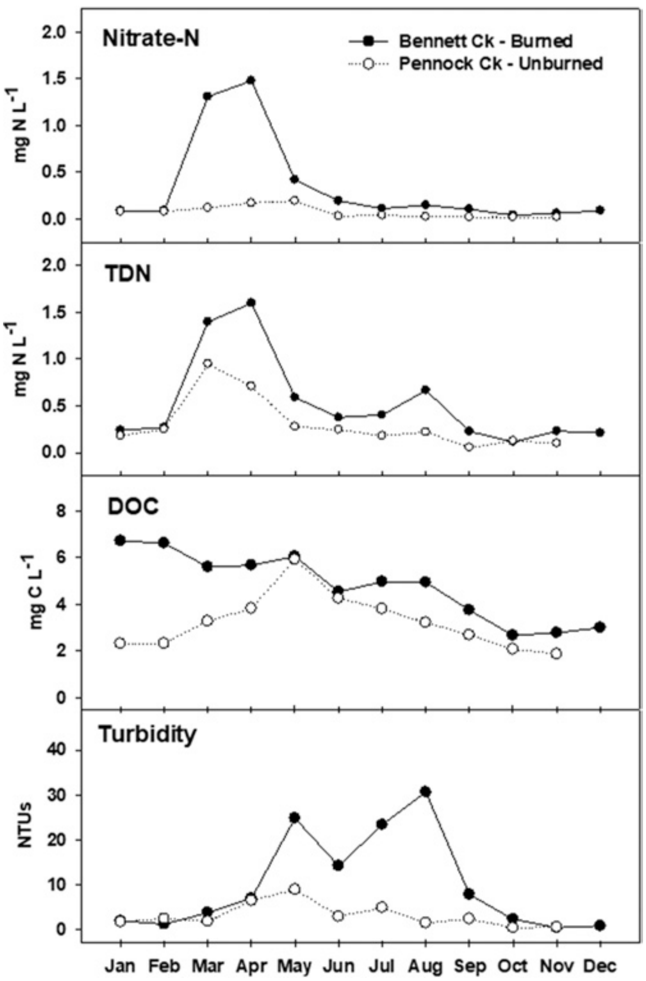

Fig. 2. Stream water quality in Bennett (70 % burned) and Pennock (84 % unburned) Creeks during 2022. Data are monthly mean concentrations.

turbidity responses in Bennett Creek, but unlike pulses during spring snowmelt they had little effect on stream C and N. There were seven summer rainstorms in 2022 with intensities > 2.54 cm /hr (I_{15}) that fell across the Cameron Peak burn scar (EFWS, Larimer County, CO 2024). These storms increased turbidity in Bennett Creek and other burned headwater tributaries and propagated downstream to the Cache la Poudre River (Rhoades et al., 2025, in review).

Soil N was generally higher on burned compared to unburned hillslopes (Table 1). Total soil N was 1.8-times higher, and the inorganic forms of plant-available N (NH_4-N and NO_3-N) were 5-times higher in the top 5 cm of burned compared to unburned soils. Inorganic N pools were also higher at the 5–15 cm soil depth, though the wildfire effect was less pronounced. Ion exchange resin (IER) NO_3-N was 3-times higher on burned compared to unburned hillslopes (see Fig. 4). Total soil C was unaffected by the fire, but owing to changes in total N, C:N was lower in burned soils. Net soil mineralization and nitrification were highly variable and often negative, and there were no consistent impacts of the wildfire on production of inorganic N.

3.2. C and N release from mulched soil columns

Woody mulch released high concentrations of DOC into soil columns, and leachate from mulched columns had significantly lower NO_3-N concentrations than unmulched columns (Fig. 3). Mulch released 777 mg L^{-1} of DOC into the soil columns on average and > 1000 mg C L^{-1} during the first rain event (data point not shown). Leachate DOC concentrations from thin (1 cm) and thickly (5 cm) mulched soil

Table 1
Soil N and C pools and net transformations on burned and unburned hillslopes measured in 2022 within the Cameron Peak fire scar. Burned hillslopes were unmulched areas in Bennett Creek watershed burned at high severity. Laboratory net mineralization and nitrification incubations were conducted at 60 % of field capacity. Symbols denote significant differences between burned and unburned hillslopes within soil depths based on one-way analysis of variance (* $p < 0.05$; ** $p < 0.005$; *** $p < 0.001$).

Depth (cm)		NH_4-N			NO_3-N			Total C		Total N			C:N			Net Mineralization		Net Nitrification	
		Mean	SD		Mean	SD		Mean	SD	Mean	SD		Mean	SD		Mean	SD	Mean	SD
		mg N kg^{-1}			mg N kg^{-1}			%		%						mg N kg^{-1} d^{-1}		mg N kg^{-1} d^{-1}	
0–5	**Unburned**	2.4	3.0	***	1.8	3.6	**	2.9	2.2	0.05	0.04	**	62.9	42.3	***	−0.16	0.31	−0.06	0.17
	Burned	11.4	8.8		9.1	7.7		2.5	1.6	0.10	0.06		26.7	10.8		−0.37	0.67	0.05	0.44
5–15	**Unburned**	1.5	0.5	*	0.8	1.4	***	1.5	0.8	0.08	0.07		35.0	42.8		0.002	0.12	0.06	0.12
	Burned	2.5	1.8		2.9	1.5		1.4	0.8	0.06	0.02		23.8	12.5		−0.063	0.15	0.04	0.11

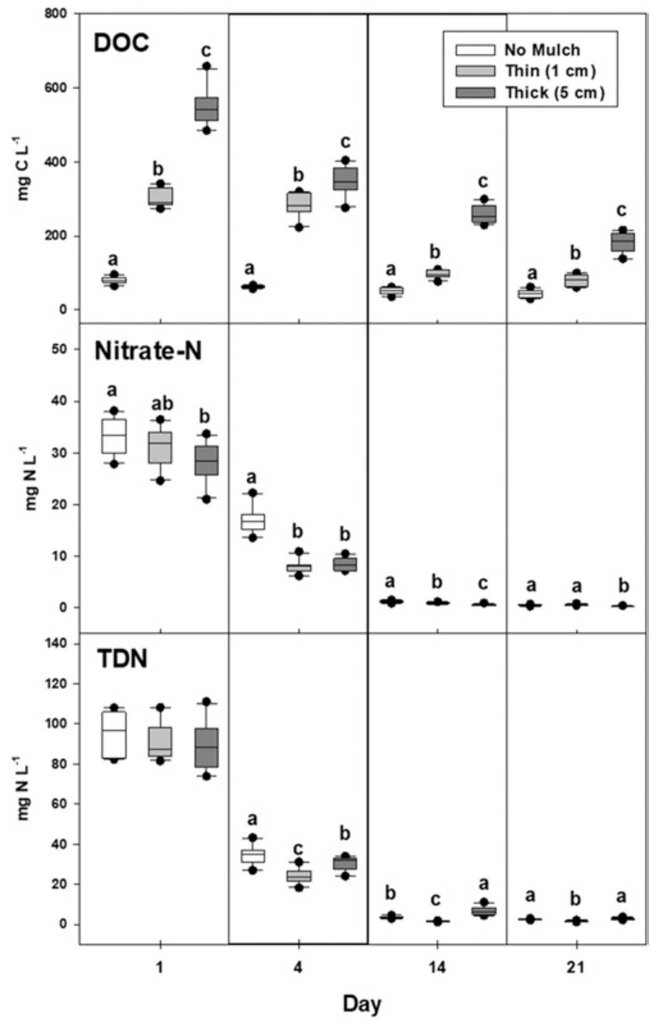

Fig. 3. Leachate DOC, nitrate-N and TDN concentrations released from soil columns during simulated rain events. The centerline of the boxplots denotes the median, the upper and lower limits span the interquartile range, the whiskers denote the 10th and 90th quartiles, and the dots beyond the whiskers are outliers. Letters denote significant differences between treatment means (n = 10 replicates per treatment) within a rain event, according to Bonferroni-adjusted Tukey's post-hoc comparisons.

columns were 303 and 547 mg C L^{-1} after the first rain event and 80 and 182 mg C L^{-1} of DOC after four storms (Fig. 3). In contrast, leachate from unmulched soil columns averaged 60 mg C L^{-1} of DOC (Fig. 3), and stream water was below 8 mg C L^{-1} in both Bennett and Pennock Creeks (Fig. 2).

Nitrate comprised > 98 % the dissolved inorganic N (NO_3-N + NH_4-N) leached from mulched soil cores and 34 % of TDN; dissolved organic N represented most of the remainder of TDN (> 60 %). Nitrate concentrations in leachate from the thin and thick mulch treatments were 22 and 27 % lower than unmulched columns on average (Fig. 3), and during some rain events, mulch decreased NO_3-N to less than half that measured in unmulched columns. Both mulch depths also reduced NH_4-N by > 85 % of concentrations in unmulched soil column leachate (data not shown). The impact of mulch on TDN was inconsistent, though like NO_3-N, its concentration declined substantially after the first two rain events. Leachate C:N (e.g., DOC:TDN) released from mulched columns was elevated compared to unmulched soils (e.g., 31 and 30 vs 9 for thin and thick mulch layers vs unmulched columns).

3.3. Mulch effects on soil N availability and moisture on burned hillslopes

As seen in our laboratory-based study, we found that mulch applied on burned hillslopes reduced soil N (Fig. 4). Ion exchange resin (IER) NO_3-N comprised 80 % of total IER-N during the snowmelt season, when its concentration and mulch-related decrease in soil N was highest. At that time, the + 1 and + 2 remulch treatments decreased IER- NO_3-N by 17 and 29 % compared to unmulched soils. In contrast, only the + 2 remulch treatment altered IER-NO_3-N during the summer season and the reduction was smaller than during snowmelt. Mulch had no effect on IER- NH_4-N during either season. Though hillslope mulching reduced IER-N, it remained nearly double that measured in unburned soils (Fig. 4).

Overall, volumetric soil moisture content (VMC) was 14 % higher on remulched hillslopes compared to controls (Fig. 5). The mulch effect was greatest (i.e., > 20 %) during the fall when soil moisture was generally driest. Conversely, there was no mulch effect during spring when moisture was relatively high. The two remulch treatments did not differ (5.1 vs 5.3 %, for +1 and +2 treatments), though VMC was significantly higher in plots where mulch cover was highest. Specifically, plots with the upper 75th percentile of mulch cover (> 56.3 %) following remulching were significantly wetter (5.9 vs 4.6 %) than those with lower mulch cover. On average, VMC was 1.4-times higher in burned

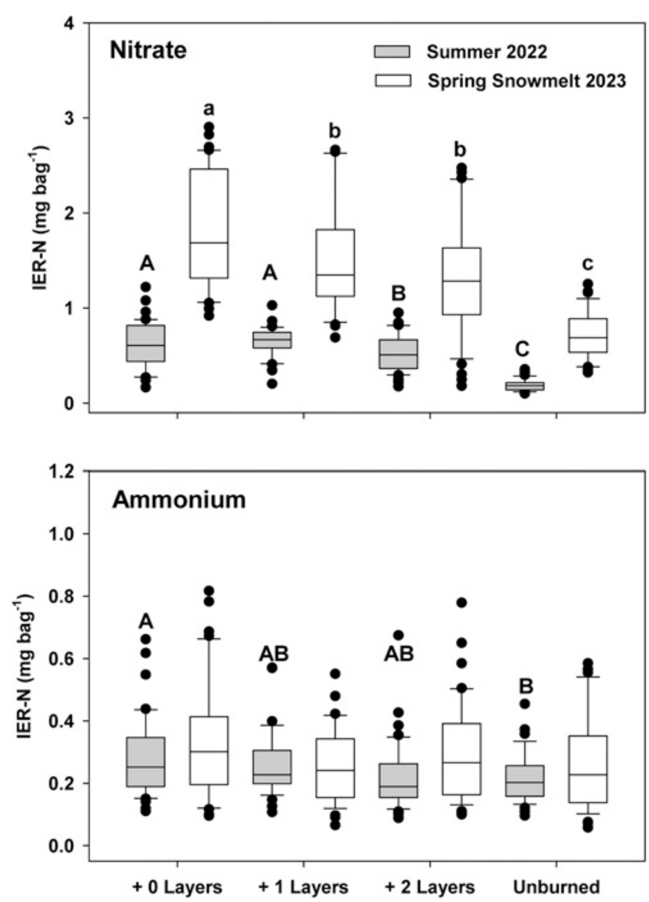

Fig. 4. Ion exchange resin nitrate (NO_3-N) and ammonium (NH_4-N) to assess soil N movement during summer 2022 (July – October) and the winter through spring snowmelt 2023 (October – May) following July 2022 remulching operations. The centerline of the box denotes median, the upper and lower limits span the interquartile range, the whiskers denote the 10th and 90th quartiles, and the dots are outliers. Letters denote significant differences between treatment means (n = 12 plot replicates per treatment) within summer (uppercase) and spring (lower case) seasons for both IER-nitrate and IER-ammonium using one way analysis of variance at α = 0.05 level.

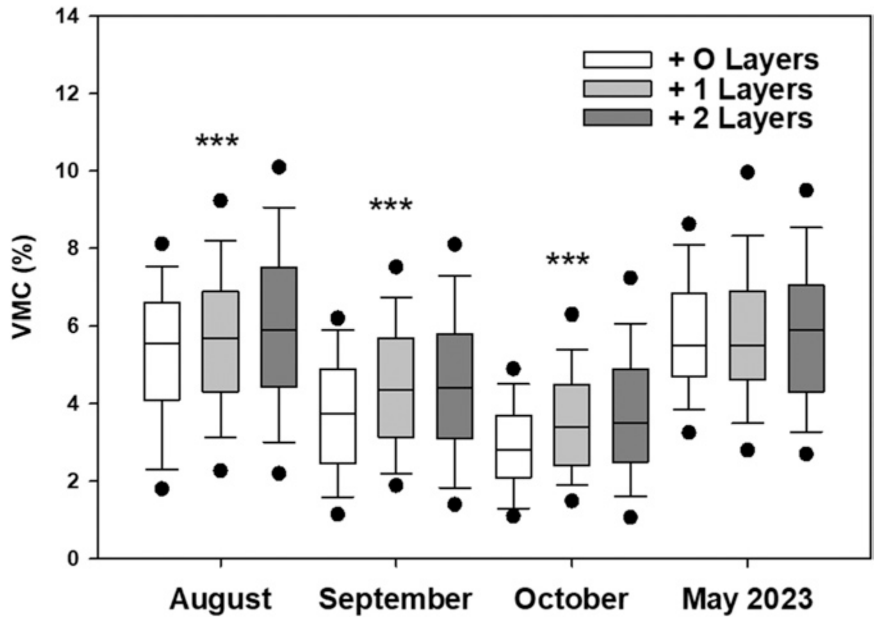

Fig. 5. Volumetric soil moisture (VMC) following July 2022 remulching operations. For monthly boxplots the centerline of the box denotes median, the upper and lower limits span the interquartile range, the whiskers and dots denote the 10th and 90th quartiles, 5th and 95th quartiles, respectively. Asterisks indicate where monthly VMC was significantly higher on the remulched hillslopes compared to controls (***, $p < 0.001$) according to Bonferroni-adjusted Tukey's post-hoc comparisons ($n = 12$ plots per treatment).

compared to unburned plots (not shown).

3.4. Consequences of post-fire mulching on stream water quality

Stream water quality in the study catchments varied among seasons and following summer rainstorms (Fig. 6). Like Bennett Creek (Fig. 2), TDN and NO_3-N peaked in the burned tributaries during the snowmelt runoff peak and then declined. The spring peak and summer decline in stream N tracked soil N availability and movement measured by ion exchange resins (Fig. 4). Dissolved organic C concentration ranged between 2 and 10 mg L^{-1} and declined rapidly after spring snowmelt. Like turbidity, both DOC and TDN were elevated in the study catchments following summer storm events, though NO_3-N was relatively unresponsive. The catchments fluctuated more seasonally and after storm events than Bennett Creek, and much more so than Pennock Creek (Fig. 2). For example, post-storm turbidity, DOC and TDN were 2–5-times higher in individual tributaries compared to Bennett Creek, and though NO_3-N did not respond following storms in Bennett Creek there were pronounced spikes in the tributaries.

Stream water quality differed between mulched and unmulched catchments though responses were closely related to pre-fire catchment differences (Table 2). Stream TDN and NO_3-N were significantly higher in the mulched catchments during snowmelt, but those catchments were also larger and had wider and more extensive valley bottoms and more stream channel heads than unmulched catchments (Table 2). In fact, average valley bottom width, the proportional extent of valleys (e.g., valley fraction) and the number of stream channel heads were all higher in the mulched catchments. Across all catchments, valley fraction and number of channel heads were well related to stream N concentrations, and they explained 22 and 25 % of the increase in snowmelt NO_3-N concentrations, respectively and 31 and 34 % of the increase in TDN.

4. Discussion

4.1. Post-fire watershed responses

Stream N, C and turbidity remained elevated in the main stem and tributaries of Bennett Creek two years after the Cameron Peak fire (Figs. 2 and 6). Overall, the fire burned 38 % of the Bennett Creek watershed at moderate and high severity (Fig. 1), though the extent of moderate and high severity was much higher in the study catchments (i.e., 80–95 %; Table 2). Spring runoff NO_3-N concentrations in Bennett Creek and its tributaries (~ 1.5 mg L^{-1}) were roughly 10-fold those in Pennock Creek, and as of spring 2024 stream NO_3-N remained elevated (0.5–1.0 mg L^{-1}) both in Bennett Creek and other streams impacted by the Cameron Peak fire (Rhoades et al., under review). Similarly, snowmelt NO_3-N concentrations commonly exceeded 1.5 mg L^{-1} in severely burned catchments for five years after the Hayman fire (Rhoades et al., 2011).

Elevated stream nutrients can persist for years to decades following wildfires burning under a wide variety of conditions (Rust et al., 2018). Like other ecosystem disturbances, the increase in post-fire stream NO_3-N results from lower plant N demand and higher mineralization of organic soil N sources (Certini, 2005; Gustine et al., 2022). In forest watersheds, NO_3-N moves from hillslopes to streams along subsurface flowpaths, primarily during spring snowmelt (Stottlemyer and Troendle, 1999). In 2022, we found that soil IER- NO_3-N was more than twice as high on burned hillslopes as unburned hillslopes during spring snowmelt (Fig. 4) and that soil moisture was higher throughout the entire growing season. Since subsurface NO_3-N transport is independent of surface runoff, post-fire stream N can remain elevated even after turbidity abates (Rhoades et al., 2019). Post-fire vegetation recovery (Rust et al., 2019) and associated nutrient uptake, especially in more mesic landscape positions has been linked to N retention and return to pre-fire water quality (Rhoades et al., 2019; Rhea et al., 2022).

4.2. Woody mulch effects on post-fire N and C

Mulch-related decreases in soil NO_3-N have been widely reported in field and laboratory trials with burned and unburned soils and in various agricultural settings (Table 3). The decrease is not universal, and responses vary among studies based on mulch rate and time since application. Determining a general mulch application rate that triggers a NO_3-N reduction is not feasible due to differences in study objectives, site conditions and analytical approaches, but based on the reviewed studies, effects were insignificant at the lowest rates studied (2.5 Mg

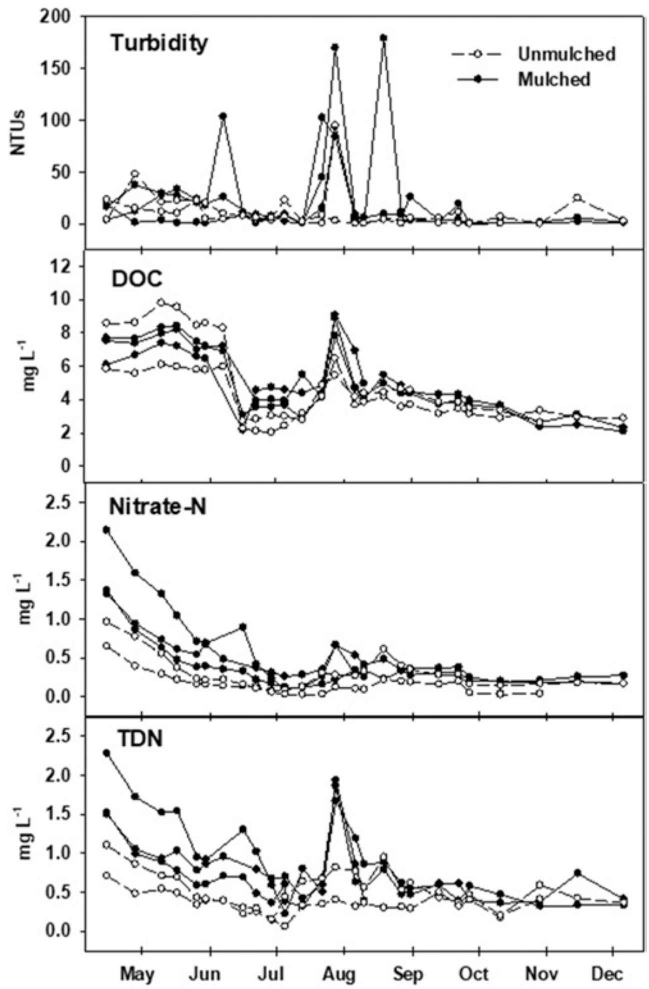

Fig. 6. Stream water quality in unmulched (n = 2) and mulched (n = 3), burned tributaries to Bennett Creek within the Cameron Peak fire, Colorado. Data are instantaneous concentrations.

ha^{-1}) and increased with mulch rate. Significant NO_3-N decreases occurred at rates as low as 5–15 Mg ha^{-1} (Reever Morghan and Seastedt, 1999; Huang et al., 2008; This study). In Canadian agricultural fields, 20 Mg ha^{-1} of wood chips was insufficient to effect soil NO_3-N or labile C, and 40 and 60 Mg ha^{-1} decreased it similarly (Uwituze et al., 2023). In unburned forest harvest areas, both 12 and 24 Mg ha^{-1} decreased NO_3-N, (Homyak et al., 2008), but similar rates (13 and 20 Mg ha^{-1}) had no effect in a burned forest (Jonas et al., 2019). In our laboratory trial, both the 1-cm mulch depth that was comparable to field applications, and the thicker treatment, reduced NO_3-N leaching significantly; the response was greater and lasted longer for the deeper mulch treatment (Fig. 3). Similarly, in experimental field plots within fuel reduction projects in various forest types, deep mulch decreased resin NO_3-N to half that measured in shallow layers (Rhoades et al., 2012).

In our study and elsewhere, operational-scale mulching rates had less effect on soil NO_3-N. None of the studies that applied straw or wood mulch at typical post-fire erosion mitigation rates (2–4 Mg ha^{-1}; Robichaud et al., 2013; Girona-García et al., 2021) reported significant decreases in soil NO_3-N (Gómez-Rey and González-Prieto, 2014, Fernández-Fernández et al., 2017; Jonas et al., 2019), though we observed a significant hillslope-scale nitrate decrease at a fairly similar rate (Fig. 4; 5 Mg ha^{-1}). In the Bennett Creek tributaries evaluated here, low mulch spatial extent and cover coupled with high topographic complexity overshadowed the NO_3-N reduction measured at smaller spatial scales (Figs. 4 and 6). High spatial variability is typical in mountainous forest ecosystems, and similar findings have been reported elsewhere. For example, despite plot-scale NO_3-N decreases in heavily mulched experimental plots, landscape-scale fuel reduction mulching significantly increased soil NO_3-N and net N mineralization 3–5 years after treatment (Rhoades et al., 2012). Though soil NO_3-N reduction is common in plot-scale mulching studies, in some instances decreasing it to pre-disturbance levels (Rhoades et al., 2015; Table 3), this has not been observed at landscape or catchment scale after wildfire or other ecosystem disturbance (Homyak et al., 2008).

Further, though high mulch application rates can reduce soil NO_3-N and leaching losses at experimental scales, the effects are short-lived. In our laboratory column study, the largest NO_3-N reductions occurred during the first two leaching events (Fig. 3). The mulch effect remained significant through the trial, but both leachate NO_3-N and treatment effects were limited after four consecutive rainfall events. Across a range of mulch studies, the influence of mulch declined rapidly in both field and laboratory trials (Table 3), and only one study reported a significant effect lasting more than 1 year (Rhoades et al., 2017). Soil NO_3-N pools and nitrification can remain elevated for many years after wildfire (Rhoades et al., 2021; Dove et al., 2020), but the high concentrations that are concern for water quality typically decrease within a few years (Covington et al., 1991; Jonas et al., 2019). Overall, though stream NO_3-N can remain elevated for many years after fire (Rust et al., 2019; Rhea et al., 2022), the likelihood of rapidly deploying sufficient mulch to elicit and maintain significant changes at operational scales seems impractical.

The most pronounced mulch effects on soil NO_3-N occurred during

Table 2
Attributes and water quality of Bennett Creek mulch study catchments. Data are mean instantaneous outlet concentrations of sampled collected weekly during spring snowmelt (i.e., April - June) 2022. Comparisons of stream water in mulched and unmulched catchments are based on one-way analysis of variance. Streamflow in catchment UE ceased in May, so stream water quality was unavailable.

Catchment		Wildfire Severity *	NDVI	Area	Valley fraction	Valley bottom width	Channel heads		Turbidity	DOC	TDN	Nitrate-N
		%		**km³**	**%**	**m**	**ha**	**#**	**NTUs**	**mg L^{-1}**		
Unmulch	**West (UW)**	90.0	0.3	1.0	0.1	30.0	16.0	16	16.9	5.0	0.5	0.4
	Mid (UM)	88.0	0.4	0.5	0.1	29.0	9.3	5	11.2	6.8	0.4	0.2
	East (UE)	95.0	0.3	0.4	0.1	10.0	28.0	12	—	—	—	—
Mulch	**West (MW)**	86.0	0.4	1.4	0.1	36.0	15.0	21	25.1	6.2	0.8	0.5
	Mid (MM)	80.0	0.3	0.6	0.2	43.0	27.1	17	4.8	5.8	1.3	1.0
	East (ME)	82.0	0.4	1.3	0.1	42.0	16.5	22	20.9	6.9	1.0	0.7
mean unmulch		91.0	0.3	0.7	0.1	23.0	17.8	11.0	14.0	5.9	0.5	0.3
mean mulch		82.7	0.3	1.1	0.2	40.3	19.5	20.0	17.0	6.3	1.0	0.7
p=									*0.069*	*0.085*	*0.004*	*< 0.001*

[*] Wildfire severity is the proportional extent of high and moderate severity.

Table 3
Mulch and C addition effects on soil nitrate (NO_3-N) in field and laboratory trials. Analytical methods, study designs and objectives varied among field and laboratory trials.

Setting	Location	Treatment	Mass Mg ha^{-1}	Soil NO_3-N Response	Duration	Comments	References
Field Trials							
Disturbed grassland	Colorado, US	Sucrose + sawdust	16.5	Decr: 67–78 %	3 months	Repeated additions over 3 yr	Reever Morghan and Seastedt (1999)
Agriculture	NE, Canada	Willow shrub chips	20, 40, 60	Decr: > 90 % (40 & 60 Mg ha^{-1})	1 year	No effect in 20 Mg ha^{-1}	Uwituze et al. (2023)
Hardwood plantation	Queensland, AUS	Mixed sp. chips	16	Decr: 56 & 63 %	1 year	Incr: gross immobilization Incr: soluble C	Huang et al. (2008)
Logging operation	New York, US	Hardwood chips	12, 24	Decr: 30 (resin), 78–100 % (extractable)	1 year	Incr: Chip N content	Homyak et al. (2008)
Mechanical fuel reduction	Colorado, US	Conifer chips	23–122	Decr: 40–50 % (thick mulch)	1 year	Incr: Chip N content No Effect at landscape scale	Rhoades et al. (2012)
Slash pile burn	Colorado, US	Conifer chips	80	Decr:73–90 %	1 year	Mulched equal to unburned	Rhoades et al. (2015)
Post-fire	Colorado, US	Lodgepole pine chips	37	Decr: 80 %	2 years	Decr: DTN by 48 %	Rhoades et al. (2017); Kaiser et al. (2024)
Post-fire	Colorado, US	Wheat straw, Wood shred + strand	13–20	No effect: straw, wood shred Incr: Wood strand	1 year	No difference among rates	Jonas et al. (2019)
Post-fire	Colorado, US	Conifer shred	5	Decr: 23 %	1 year	Larger effect during snowmelt No effect at watershed	This study
Laboratory Trials							
Post-fire	NW, Spain	Barley straw	2.5	No effect	6 mo	Decr NO_3-N immobilization	Fernandez-Fernandez et al. (2017)
Post-fire	NW, Spain	Barley straw	2.5	No Effect	1 year	Return to baseline: 8mo	Gomez-Rey and Gozalez-Prieto (2014)
Post-fire	NW, Spain	Barley straw	2.5	No Effect	7 days	Decr NO_3-N immobilization	Gomez-Rey and Gozalez-Prieto (2015)
Agriculture	Alberta, Canada	Wheat straw	~4	Decr: 22 %	12 days	Incr NO_3-N immobilization	Cheng et al., (2012)
Post-fire	Colorado, US	Conifer shred	14, 70	Decr: 22–27 %	1 month	Response tracked rate	This study

spring snowmelt when soil moisture and NO_3-N concentrations were highest (Fig. 4 & 5) and when both subsurface transport from hillslopes and stream export are greatest (Stieglitz et al., 2003). In the Rocky Mountains, plant-available N generated during the winter months (Yano et al., 2019) is transported along subsurface flowpaths during spring snowmelt (Mast et al., 2016). The decreased soil leachate NO_3-N we observed has been attributed to stimulation of microbial growth and N immobilization by C inputs from mulch (Uddin et al., 2020). While our laboratory column study optimized N retention by combining high DOC levels and a stable soil environment, we observed the same general pattern on the much more heterogeneous hillslopes. Though high DOC and NO_3-N can also promote N loss in anoxic soils through denitrification (Schipper and Vojvodic-Vukovic, 1998), this was unlikely to have been a significant cause of N loss from the aerobic soil columns or well-drained hillslope soils at our study sites.

Severe wildfires can have long-lasting impacts on vegetation, soils and the microbial processes that regulate and retain N (Dove et al., 2020; Nelson et al., 2022; Caiafa et al., 2023). Mulching is known to stimulate short-term soil microbial responses (Carmona-Yañez et al., 2023; Ortega et al., 2023) and has potential to influence longer-term ecosystem trajectories. Following the 2010 Church's Park fire in central Colorado, wood mulch persisted for 10 years after application on burned hillslopes, and had lasting impacts on soil moisture, the microbiome and plant species composition, but not N cycling (Kaiser et al., 2024). Elsewhere in Colorado, mulch applied as part of fuel reduction or pile burn rehabilitation projects reduced soil NO_3-N, the first year after treatment but did not persist the second year (Rhoades et al., 2012 and 2015). Though NO_3-N concentrations decreased rapidly following sequential rainfall events (Fig. 3), DOC remained relatively high. Others have shown that mulch may generate DOC for up to seven years (Abusallout and Hua, 2017; Pitman and Peace, 2021). Though the influence of mulch on NO_3-N retention may be transitory, elevated soil moisture and DOC inputs beneath mulch may impact soil microbes, favor plant recovery (Jonas et al., 2019) and enhance plant N uptake and watershed nutrient retention.

The potential benefits of mulching on soil N and stream N losses are attributed to stimulation of microbial activity by labile C contained in DOC (Perry et al., 2010; Uddin et al., 2020). The amount and composition of C supplied to drinking water treatment facilities are closely monitored since this controls the formation of disinfection by-products (DBPs) that are concerns for human health (Hohner et al., 2019). Wildfires can increase, decrease or have no effect on stream DOC (Santos et al., 2019; Uzun et al., 2020; Rodríguez-Cardona et al., 2020) with responses that vary among ecosystems, burn severity and time since fire (Chow et al., 2019). If mulch is a significant additional source of DOC, this management intervention could exacerbate post-fire concerns about DBP formation. Though we observed sustained, elevated DOC concentrations in soil core leachate (Fig. 3), we found no evidence that operational-scale mulching increased DOC in streams draining burned catchments (Fig. 6). However, since mulch can release DOC for nearly a decade (Abusallout and Hua, 2017; Pitman and Peace, 2021), this long-term aspect of the management treatment is worth further study.

5. Conclusions and management implications

This evaluation of the biogeochemical effects of woody mulch advances our understanding of the potential benefits, but also the practical limitations of this treatment to address post-fire water quality concerns. We document the potential for woody mulch to reduce post-fire NO_3-N leaching and inorganic soil N availability, though not to the levels measured in unburned soils. Further, the patterns we found in laboratory soil columns and hillslope-scale plots were not detectable at the catchment scale. The low application rate and limited extent of mulching combined with high topographic and geomorphic variability exceeded the ability to detect stream N responses to the treatment. The operational-scale application rate in this study was well below the minimum mulch cover recommended to treat post-fire erosion (Robichaud et al., 2013; Girona-García et al., 2021). Considering that the study catchments were mulched at < 10 % of the rate recommended to control erosion, it is not surprising that hillslope erosion (Hayter, 2023) and biogeochemical responses were both undetectable. Though this replicated, catchment-scale experiment created an opportunity to evaluate the utility of this post-fire rehabilitation treatment, operational constraints prevented an adequate test of the treatment.

Given the high cost and operational limits associated with aerial mulching, managers may consider prioritizing sensitive and high-value locations. Our findings demonstrate that adequate mulch cover can influence short-term N losses from burned soils and hillslopes. However, the effects of mulch on soil organic matter losses (Keizer et al., 2018), soil moisture (Kaiser et al., 2024) and plant recovery (Jonas et al., 2019) have potential long-term biogeochemical impacts on ecosystem N retention. We also found that watersheds with greater size, slope and valley fraction had higher stream NO_3-N. Future research could further explore catchment characteristics associated with increased post-fire stream responses to help select candidate locations for focused mulch applications. Though logistically challenging, mulching shortly after fire, in advance of high intensity rainstorms, may improve mulch longevity and treatment effectiveness. Post-fire rehabilitation efforts aimed at protecting surface water quality may benefit from prioritizing sensitive watershed locations and treating them with adequate mulch.

CRediT authorship contribution statement

Charles C. Rhoades: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Mikaela J. Richardson:** Writing – review & editing, Investigation. **Timothy S. Fegel:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Stephanie K. Kampf:** Writing – review & editing, Supervision, Methodology, Funding acquisition, 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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