THESIS

EVALUATING POST-FIRE WOODY MULCH EFFECTS ON SOIL AND STREAM NITROGEN

Submitted by

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ABSTRACT

EVALUATING POST-FIRE WOODY MULCH EFFECTS ON SOIL AND STREAM NITROGEN

Severe wildfires often increase nitrogen (N) loss from burned watersheds, impacting downstream water quality, water treatability, and aquatic habitat. Woody mulch is commonly applied to mitigate soil erosion and enhance revegetation post-fire, but it also provides a source of labile carbon (C) that may stimulate microbial immobilization and limit N release from soils. The objective of our study was to evaluate whether mulch application influenced turnover and loss of soil C and N in laboratory leaching trials and hillslope field settings, and then compared post-fire C and N in streams draining mulched and unmulched catchments. In the laboratory, we quantified C and N inputs and leaching outputs from mulched and unmulched soil columns. Within the Cameron Peak fire burn scar in northern Colorado, we compared soil N availability and potential leaching losses between mulched and unmulched hillslope plots. We also measured C, N, and other chemical constituents in streams draining three mulched and three unmulched catchments. In the laboratory leaching studies, mulch added high concentrations of dissolved organic carbon (> 500 mg L^{-1}) and decreased nitrate leaching from soil columns by 27% during repeated simulated rainfall events. In hillslope plots, mulching also reduced soil nitrate, with greater impacts following spring snowmelt when N losses from soils to streams was highest. However, the effect of mulching was not measurable at the catchment scale due to low application rates and mulch extent, paired with high topographic and geomorphic variability amongst the catchments. Our findings show that C inputs from woody mulch can influence soil

N retention in burned watersheds when applied at a minimum rate of 5 Mg ha^{-1}; however practical constraints on aerial application may make it challenging to apply enough mulch for any downstream response to be detectable. Coupled with physical erosion protection, the biogeochemical impacts of mulching may facilitate soil and vegetation recovery following severe wildfire and reduce post-fire N losses to streams if sufficiently applied. Therefore, further post-fire rehabilitation efforts should optimize mulch operations by prioritizing sensitive watersheds and treating them with adequate mulch.

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Finally, none of this could have been done without the unconditional support and love of my family and dear friends, near and far. Thank you for the unwavering encouragement throughout this process.

DEDICATION

I would like to dedicate this work to my dear aunt, Ruby Ann Richardson, who lost the fight to cancer amidst my time in graduate school. Your resiliency, pure grit, and infectious joy motivated me to persevere throughout this graduate journey. I owe much of my determination to your memory, which I will continue to carry with me as I embark on the next chapter of life.

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1. INTRODUCTION

In western North America, severe wildfires have increased in frequency, severity, and size over the last four decades (Dennison et al., 2014; Westerling, 2016; Weber et al., 2020). These trends, attributed to rising temperatures (Harvey, 2016; Jones et al., 2022), earlier spring snowmelt (Westerling, 2016), and other factors, are anticipated to continue in the future. Some concerns about increasing wildfire activity include the prolonged and significant effects on forested watersheds and soils (Certini, 2005; Hohner et al., 2019; Rhoades et al., 2011; Smith et al., 2011). Wildfire combustion of forest biomass and organic surface layers can increase nutrient availability in soils by reducing plant nutrient and water demand (Certini, 2005). This increases inorganic soil nitrogen (N) concentrations (Andreu et al., 1996; Covington et al., 1991; Murphy et al., 2006) and the leaching of soluble nitrogen, particularly nitrate, into streams (Rust et al., 2019). Both nitrogen and phosphorus export to streams can increase post-fire (Paul et al., 2022), primarily during the first few years (Rust et al., 2018).

However, wildfire impacts on soil and stream N can persist for many years (Kurth et al., 2014; Rhea et al., 2021; Rhoades et al., 2019; Rust et al., 2018). For example, nitrate production via nitrification can remain elevated for years to more than three decades after stand-replacing wildfires (Dove et al., 2020; Kurth et al., 2014). After the Hayman fire in central Colorado, stream nitrate and total dissolved N (TDN) remained elevated for 14 years in burned catchments relative to unburned areas and pre-burn conditions (Rhoades et al., 2019). Rehabilitating the soil processes that regulate soil N availability and nitrate leaching has the potential to reduce persistent post-fire N loading to streams.

Post-fire restoration treatments, such as woody mulch applications, have been utilized to reduce soil erosion and water quality impairment (Prats et al., 2016; Robichaud et al., 2013).

These treatments also help to reestablish plant and organic soil cover and to moderate soil N cycling (Rhoades et al., 2017). Prior studies show that woody mulch depresses inorganic soil N levels (Homyak et al., 2008; Rhoades et al., 2012; Rhoades et al., 2017) and may mitigate post-fire N release to streams. Labile carbon (C) released from mulch can stimulate soil microbial activity and the N demand that incorporates (e.g. immobilizes) inorganic N into microbial biomass, thus reducing its levels in the soil (Averett et al., 2004; Blumenthal et al., 2003; Prober et al., 2005; Uddin et al., 2020). These prior studies demonstrate mulch impacts at plot and hillslope scales, but limited information is available on whether it also has the potential to reduce post-fire N losses to streams and have measurable impacts on waters downstream of burned forests.

To address this knowledge gap, we evaluated the potential for mulch to alter N losses from burned soils at multiple spatial scales, spanning from controlled laboratory studies to mulched hillslopes and catchments. Mulch was applied within the 2020 Cameron Peak fire burn area in northern Colorado, where approximately 4,040 ha were treated between 2021 and 2022 at a cost of \$6000 ha^{-1} (CPRW, pers. comm.). First, to evaluate the potential for mulch to alter soil N leaching, we conducted a laboratory column study to simulate how a standard mulch addition and uniform rainfall affect C and N inputs and outputs. We then compared inorganic soil N and potential N leaching between burned plots on hillslopes that received different mulch application rates. To evaluate the catchment-scale consequences of the mulch treatments, we measured stream water chemistry in replicated mulched and unmulched headwater catchments. Finally, we characterized the influence of wildfire on soil and stream C and N. We expect that mulch treatments will reduce soil N and nitrate leaching, as has been reported in other studies but hypothesize that our ability to detect mulch impacts will decrease with greater heterogeneity at larger hillslope and catchment scales. This study will help elucidate the potential for post-fire mulching to influence water quality at operational scales relevant to downstream uses.

2. METHODS

2.1 Site Description

Research was conducted within the burn scar of the 2020 Cameron Peak fire, Colorado's largest wildfire, which burned 84,545 ha of the Arapaho and Roosevelt National Forest in Larimer and Jackson Counties and Rocky Mountain National Park (Figure 1) (Larimer County et al., 2021). Six adjoining headwater catchments with generally similar burn severity, contributing area, and slope were selected to assess the influence of post-wildfire mulch on erosion (Hayter, 2023) and water quality (Figure 2A). The catchments drain into Bennett Creek, a tributary of the South Fork of the Cache la Poudre River. Their contributing areas range from 0.57 – 1.49 km^2 and elevations between 2342 and 2779 m (Table 1). On average, the catchments were burned at 76% and 11% moderate and high severity (BAER, 2023) (Table 1). For comparison, 31% and 6% of the entire Cameron Peak fire burned at moderate and high severity (BAER, 2023). Prior to the fire, the site 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 rock, gneiss, and schist parent material (Shaver et al., 1988; Web Soil Survey, 2023). The soil profile extends to 50 cm in depth (Web Soil Survey, 2023). The study site receives an average of 470 mm of precipitation annually (PRISM Climate Group, 2023) as snow and rain, including high-intensity convective summer storms.

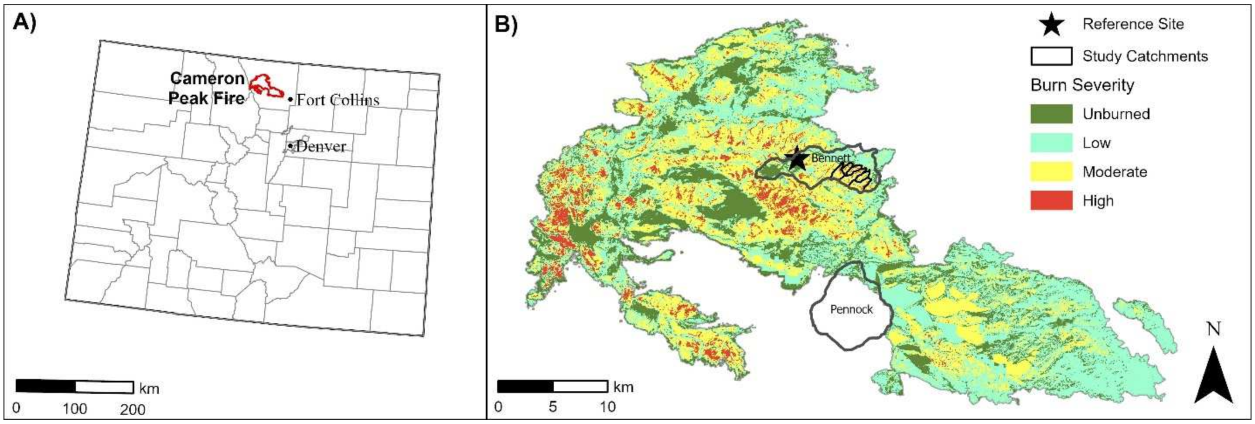


Figure 1. A) The 2020 Cameron Peak fire perimeter (red outline) within the State of Colorado, USA. B) Burn severity (BAER, 2020) with the six Bennett Creek study catchments (black outline), the unburned hillslope reference site (black star), and the Bennett and Pennock Creek watersheds (gray outline).

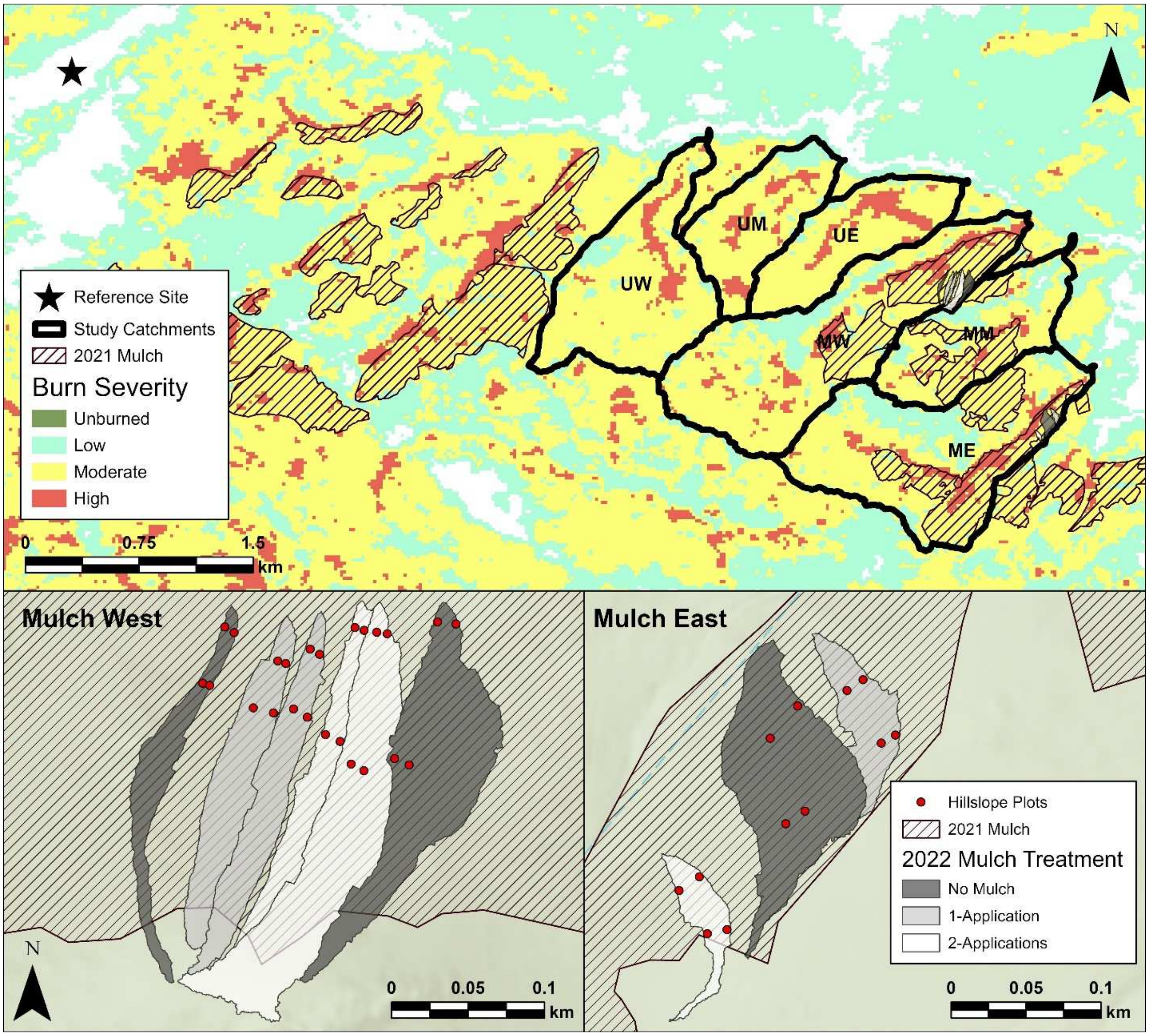


Figure 2. A) The six Bennett Creek study catchments (black outline), the unburned hillslope reference site (black star), and the hillslope sites that received additional wood mulch in 2022 (red outline). Woody mulch was applied aerially in 2021 to brown-hatched polygons. B-C) Hillslope areas that received no mulch, 1 or 2 additional mulch applications in 2022. Study plots are indicated by the red dots.

Table 1. Characteristics of study catchments in the Bennett Creek watershed. Slope was calculated using Lidar data (USGS, 2023). Burn severity was calculated from remotely sensed soil burn severity classifications (BAER, 2023). Normalized difference vegetation index (NDVI) was estimated in August 2022 using Landsat 8 imagery (USGS, 2023). Mulch treatment area is the proportion of a catchment designated to receive aerial mulch (Figure 2), not the surficial cover of mulch.

Catchment	Contributing Area	Mean Slope	Low Severity	Moderate Severity	High Severity	Mulch Treatment	NDVI
	(km^2)	(%)					
MW	1.5	29	15	74	12	33	0.36
MM	0.71	29	20	74	6.0	31	0.32
ME	1.4	26	18	71	11	23	0.37
UW	1.0	26	11	81	8.0	0	0.34
UM	0.57	25	11	74	14	0	0.39
UE	0.62	28	5.0	80	15	0	0.32

2.2 Aerial Mulching

Approximately 340 ha of the Bennett Creek watershed was aerially mulched in July and August 2021 with material sourced from locally salvaged burned trees. Mulch was comprised of wood shred pieces (10-20 cm in length, <2.5 cm in diameter), with minimal fine particles (JW Associates, pers. comm.). Mulch was applied to three study catchments; three adjacent catchments were left unmulched (Figure 2A). The portions of the catchments selected for mulching had high or moderate burn severity, slopes from 20 to 60%, and were without extensive exposed rock or dense post-fire vegetation regrowth. Overall, these areas comprised 29% of the study catchments. Extensive research has established that 70% mulch cover provides effective post-fire erosion control (Girona-García et al., 2021; Robichaud et al., 2013), and this was the target cover designated for treatments in the study catchments and across the Cameron Peak fire (JW Associates, pers. comm.).

After the mulch applications, we quantified mulch, bare soil, rock, vegetation, and coarse wood cover within 50 cm^2 quadrats (n = 92) along transects evenly spaced within designated mulch treatment areas. Mulch cover was 22% on average (maximum: 84%) and reached the 70%

target cover threshold in 8% of the quadrats. Combining the extent of designated mulch areas within the study catchment (29%) and the average cover within them (22%), we estimate that mulch cover was only 6% across the three study catchments. Using an estimated mulch bulk density (0.13 g cm^{-3}; n =5) and the average mulch cover (22%), this equated to a mulch mass of 2.1 Mg ha^{-1}.

Due to the low mulch cover within the study catchments, in July 2022 we established a hillslope-scale trial with additional mulch applications (Figure 2). Either zero, one, or two applications of wood mulch were applied aerially to three hillslope replicates in areas that had low original mulch cover (Figure 2A). Three unburned hillslope replicates also were selected nearby within the Bennett Creek watershed (Figure 2A). We established four 2 x 2 m plots within each hillslope replicate (n = 12 plots per treatment).

Within the burned plots (Figure 2B,C), mulch, bare soil, rock, vegetation, and wood cover were estimated in 1 m^2 quadrats during two separate surveys conducted one day and one month after mulching (Figure 3). The repeat sampling enabled capturing short-term changes in mulch cover during the summer monsoon season. Initial mulch cover in the hillslope plots differed little between the two application levels (36 vs 40%; Table 2) and had an average depth of 0.92 cm. Maximum mulch cover reached 100%, but similar to earlier treatments, few quadrats (6%; n = 36) reached the 70% target cover threshold. Mulch masses, calculated as described above, were 4.9 and 5.4 Mg ha^{-1} for the 1 and 2-applications (Table 2) After one month, mulch cover declined to 24 and 35% in the one-application and two-applications plots (Figure 3).

Table 2. Woody mulch applied in laboratory and field studies following the 2020 Cameron Peak fire, Colorado. Hillslope and catchment mulch cover was estimated with designated mulch application areas.

Spatial Scale	Amendment	Wood Mulch			
		Mass	**C Content**	**N Content**	**Cover**
		(Mg ha^{-1})			(%)
Soil Columns	Thin (1 cm)	15.3	7.5	0.03	100
	Thick (5 cm)	76.4	37.4	0.17	100
Hillslope Plots	1-Application	4.9	2.4	0.02	36
	2-Applications	5.4	2.6	0.02	40
Catchment	--	2.1	1.0	0.01	22*

*Mulch cover was 6% at the catchment scale, since only 29% of the study catchments were designated for mulching.

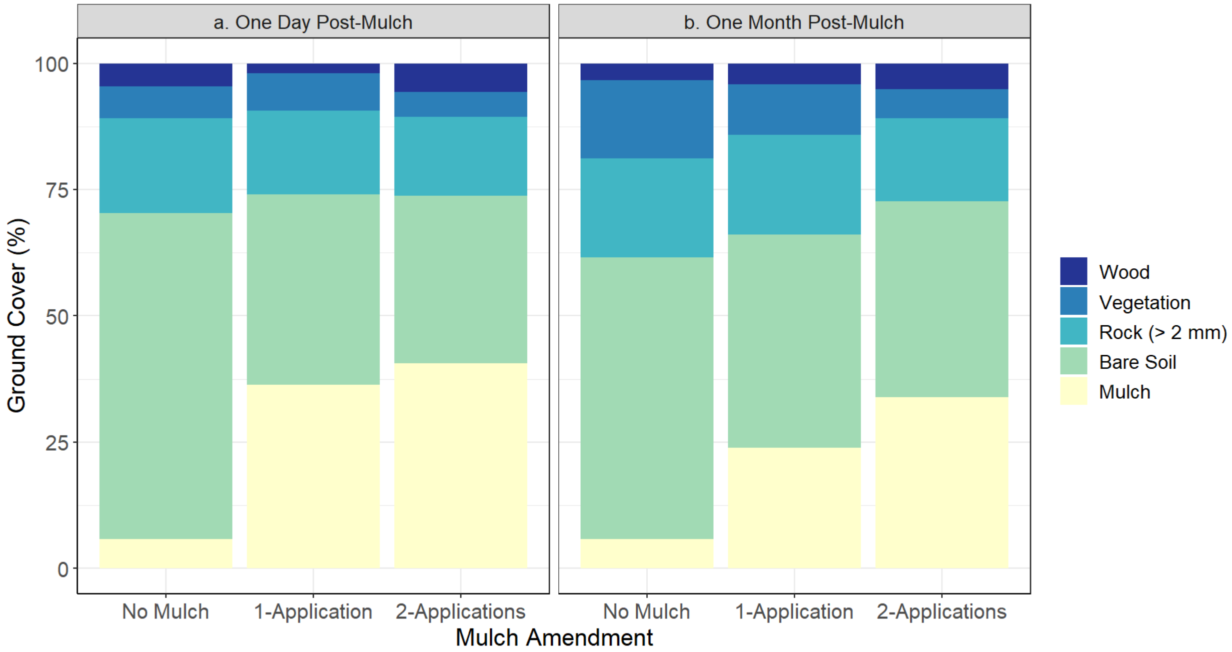


Figure 3. Average ground cover in hillslope plots (n = 12 plots per treatment) measured after 2022 mulch application following the 2020 Cameron Peak fire, Colorado. A limited amount (6% cover) of mulch from 2021 catchment-scale applications was present within the plots that received "No Mulch" treatments in 2022. Cover was measured one day and one month after mulching to evaluate the short term redistribution of mulch from summer rainstorms.

2.3 C and N Leaching from Mulched Soil Columns

Laboratory column leaching experiments were conducted to quantify how C inputs from mulch influence soil nitrate leaching. Soil columns received thin (1 cm) and thick (5 cm) mulch treatments that were compared to unmulched soils. The depth of the thin treatment was comparable to that measured in the field. The mulch masses equated to 15.3 Mg ha^{-1} and 76.4 Mg ha^{-1}, respectively, for the thin and thick mulch treatments. Ten replicates of each treatment were set up with 50 g soil samples placed in column specimen cups with a 1.2 µm glass microfiber filter paper at the bottom to avoid soil particles from passing through. Mulch was passed through a 3.35 mm mesh sieve before it was added on the soil columns. To simulate rainfall and subsequent leachings over the course of two summer months in the study area, we conducted four average rainfall events by adding 25 mL of DI water to each soil column (i.e., 20 mm, 3 h rainfall event; NOAA, 2024). Consecutive rainfall events were conducted on weekly intervals, and leachate was collected from the specimen cups. Soil columns were loosely covered to reduce soil and mulch drying and maintained at uniform 20°C between events. We also quantified C inputs from mulch to the soil columns by collecting leachate in specimen cups with mulch only. The columns received the same consecutive wetting regimen as described above.

Dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) measurements in leachate samples were performed via high-temperature combustion catalytic oxidation using a Shimazdu TOC-V_{CPN} total organic C/N analyzer with 2 M HCl addition before analysis to remove mineral C (Shimazdu Corporation, Columbia, MD). Detection limits for DOC and TDN were 50 µg L^{-1}. Leachate NO_3-N and NH_4-N concentrations were determined by ion chromatography via electrical conductivity detection, using an AS19A Anion-Exchange column for anions and a CS12A Cation-Exchange column for cations (Thermo Fisher, Waltham, MA). Detection limits for NO_3-N was 11 µg $L^{-1}$and NH_4-N was 39 µg L^{-1}. Masses of leached N (TDN, NO_3-N, and NH_4-N) and C from the soil columns over the course of the rainfall trail were calculated by multiplying the concentrations by the leachate volume (20 mL) collected for each event.

We also characterized the C and N content of mineral soil and woody mulch used in the column study for comparison with that lost in the leachate. Mineral soil samples collected from unmulched hillslopes within the Bennett Creek watershed (0-5 depth) in July 2022 were analyzed for gravimetric moisture content, total soil C and N, and inorganic soil N. Gravimetric moisture content was used to convert nutrient concentrations to a dry soil mass basis and calculated as the water lost from 10g soil subsamples (n = 6) that were oven-dried at 60°C for 48 hours. The dried subsamples were ground to a fine powder and analyzed for total C and N on a CN802 Elemental Analyzer (Velp Scientifica, Deer Park, NY, USA). Subsamples of sieved mulch were ground to a fine powder and analyzed for total C and N as described above.

2.4 Fire Effects on Hillslope-Scale Soil C and N

We characterized the influence of wildfire on soil C and N stocks, N transformations and leaching potential by comparing relatively lightly mulched hillslope plots (i.e., 6% cover) and unburned reference sites. Two mineral soil cores were collected from each burned and unburned plot (n = 48) and divided into two depths (0-5 and 5-15 cm). Samples were collected prior to the additional 2022 mulch applications (Figure 2). Rocks and roots were removed from the samples by hand, and samples were then stored at 4°C until extraction (< 7 days).

We extracted inorganic N forms, ammonium (NH_4-N) and nitrate (NO_3-N), conducted 21-day aerobic mineralization and nitrification assays, and measured total N and C pools as follows. Initial extractable soil inorganic nitrogen was measured by extracting 20 g subsamples of mineral soil with 100mL of 2M KCl, shaking for 60 minutes, filtering through 1.2 µm glass microfiber filter paper, and analyzing for NO_3-N and NH_4-N by colorimetric spectrophotometry on FIA8000+ flow injection analyzer (Lachat Company, Loveland, CO, USA). Detection limits for extractable soil NO_3-N and NH_4-N were 50 µg L^{-1}. A second 20 g subsample of soil was placed in a 120 mL plastic cup and wetted to 60% of field capacity. Samples were loosely capped, incubated at 20°C and rewetted periodically. At the end of the incubation, soil samples were extracted and analyzed for NO_3^- and NH_4^+ as described above. Net transformations were calculated as: net mineralization = $(NO_3\text{-N} + NH_4\text{-N})t_{21\text{ d}} - (NO_3\text{-N} + NH_4\text{-N})t_0$; net nitrification = $(NO_3\text{-N})t_{21\text{ d}} - (NO_3\text{-N})t_0$. A 10 g subsample was oven-dried at 105°C for 24 hours to determine gravimetric soil water content to report nutrient concentrations on a dry soil mass basis. After drying, the subsamples were passed through a 2 mm sieve, ground to a fine powder, and analyzed for soil N and C as described above.

2.5 Mulch Impacts on Hillslope-Scale Soil N Availability and Soil Moisture

We evaluated the effects of wildfire and woody mulch treatments on soil nutrients and water content within the hillslope plots (Figure 2). We measured plant-available soil nitrate and potential nitrate leaching using ion exchange resin (IER) bags (Binkley & Matson, 1983). The bags are constructed using 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 nitrate and ammonium. Three IER bags were inserted 5-10cm deep into mineral soil in each hillslope plot. Burned sites contained no organic horizon; the unburned reference site had a 7-10 cm thick organic horizon. IER bags were deployed at the beginning of the summer and winter seasons after the 2022 mulch application to collect inorganic N mobilized by summer rain events and spring snowmelt. At the end of each deployment period, IER bags were collected and stored cool until processing. Samples were extracted with 100 mL of 2M KCl, shaken for 60 minutes, and filtered through 1.2 µm glass microfiber filter paper, and frozen until analysis. Nitrate and ammonium concentrations were measured by spectrophotometry with a flow injection analyzer (Lachat Company, Loveland, CO). Detection limits for IER extracted NO_3-N and NH_4-N were 50 µg L^{-1}. Values were corrected with field and lab blanks, screened for outliers based on being greater than 2 standard deviations above the mean, and averaged by plot.

Volumetric soil water content (VWC) (0-10 cm depth) was measured in the hillslope-scale plots and unburned reference areas weekly from June through August and biweekly from September through November of 2022 using a hand-held (CD 620, HydroSense Campbell Scientific, Logan, UT). Nine measurements were recorded per plot beneath surface mulch or organic soil layers, and the values were averaged by plot. Prior to the application of the 2022 hillslope scale mulch, VWC was only measured in one of the hillslope study areas (MW; Figure 2B).

2.6 Consequences of Operational-Scale Mulching on Stream C and N

We analyzed stream water C and N concentrations in the three mulched and three unmulched study catchments, along with samples from the main stem of Bennett Creek and Pennock Creek, a primarily unburned tributary (Figure 1B). Stream water was sampled weekly (April to August) and biweekly (September to October) through 2022. Samples were collected in HDPE plastic bottles and stored cold. Within 48 hours, water subsamples were filtered through a 0.7µm glass microfiber filter paper to be analyzed for dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) as described above for the soil column leachate samples. Additional subsamples were filtered through a 0.45 µm glass microfiber filter paper to be analyzed for inorganic nutrient concentrations as described above for the soil column leachate samples.

Topographic, surface cover, fire severity, and geomorphic metrics were characterized for each study catchment to evaluate how they related to stream C and N concentrations. Topographic attributes included average slope and contributing catchment area. Average slope values were calculated using Lidar digital elevation models from the USGS National Map 3D Elevation Program (USGS, 2023). Cover variables were vegetation and bedrock fraction. Vegetation greenness was estimated using the normalized differenced vegetation index (NDVI) from Landsat 8 imagery for August 2022. The fractional extent of bedrock outcrops was digitized and quantified within each catchment. Burn severity was assessed from remotely sensed soil burn severity classifications (BAER, 2023). Geomorphic metrics included the volume and length of erosion pathways, valley fraction, and mean index of connectivity. Erosion pathways were digitized from the elevation differences between digital elevation models derived from drone flights in May and October 2022 (Hayter, 2023); these pathways were evident as paths of decreased elevation that follow drainage lines. The total length and volume of these erosion pathways were computed for each catchment. The fraction of each catchment that is valley or hollow was determined using the geomorphon approach calculated in Whitebox tools (Jasiewicz and Stepinski, 2013). This approach divides landscapes into geomorphic units based on fine-resolution topographic data. The index of connectivity was calculated from 1 m resolution Lidar data (Borselli et al., 2008). This index uses slope and flow accumulation characteristics to compute the likelihood that watersheds have connectivity between hillslopes and streams.

2.7 Data Analysis

We evaluated whether mulching had significant impacts on leachate, soil, and streamwater C and N at the various spatial scales. The choice of statistical test depended on the probability distribution of the data at each scale. For the soil column laboratory experiments and hillslope plot measurements, data were either normally or log-normally distributed, so data were log-transformed, as needed, prior to analyses to meet assumptions of normality and homogeneity of variance. We evaluated the effect of mulch treatment on leachate C and nitrate during consecutive rainfall events using a two-way mixed analysis of variance. At the hillslope scale, we tested the effect of mulch treatment within seasons on total IER-N and nitrate means using a one-way analysis of variance. We evaluated whether volumetric soil moisture differed by hillslope-scale mulch treatment and by percent mulch cover after the supplemental 2022 mulching using a one-way analysis of variance. Statistical significance was set for p-values less than $\alpha = 0.05$, and post hoc comparisons were made with Tukey Bonferroni adjusted p-values.

Stream C and N seasonal mean concentrations were not normally distributed, even after data transformations, so we compared study catchments, Bennett and Pennock Creeks using non-parametric Kruskal-Wallis means comparisons within seasons. Seasonal divisions were based on the falling and rising limbs of the streamflow hydrograph and characterized as spring (April to mid-June) and summer (mid-June to August). Statistical significance was set for p-values less than $\alpha = 0.05$, and post hoc comparisons were made with Dunn Test, Holm-Bonferroni adjusted p-values. We calculated Pearson correlations between stream N and C and predictor variables using seasonal concentration means with the R “stats” package (R Core Team, 2022). All statistical analyses were conducted in R (R Core Team, 2022).

3. RESULTS

3.1 C and N Leaching from Mulched Soil Columns

The mulch soil columns leached more DOC than unmulched burned soils throughout the simulated rainfall trial (Figure 4). During the consecutive simulated rain events, DOC leached was 82% and 43% higher from the thick and thin mulched soils than from the unmulched soil. Over the course of the study, leachate DOC was between 180 to 550 mg C L^{-1} beneath thickly mulched soils and ranged from 100 to 300 mg C L^{-1} in the thin mulch treatment (Figure 4). Comparatively, leachate DOC in unmulched soil was between 43 to 80 mg C L^{-1}. During the trial, 27 and 15 mg of C was exported as DOC from the thick and thin mulch treated soil columns, compared to 4.7 mg from the unmulched soil columns. Concentrations decreased with consecutive rain events, but DOC loss from the thin and thick mulched soils remained roughly 2 and 4-times higher at the end of the trial.

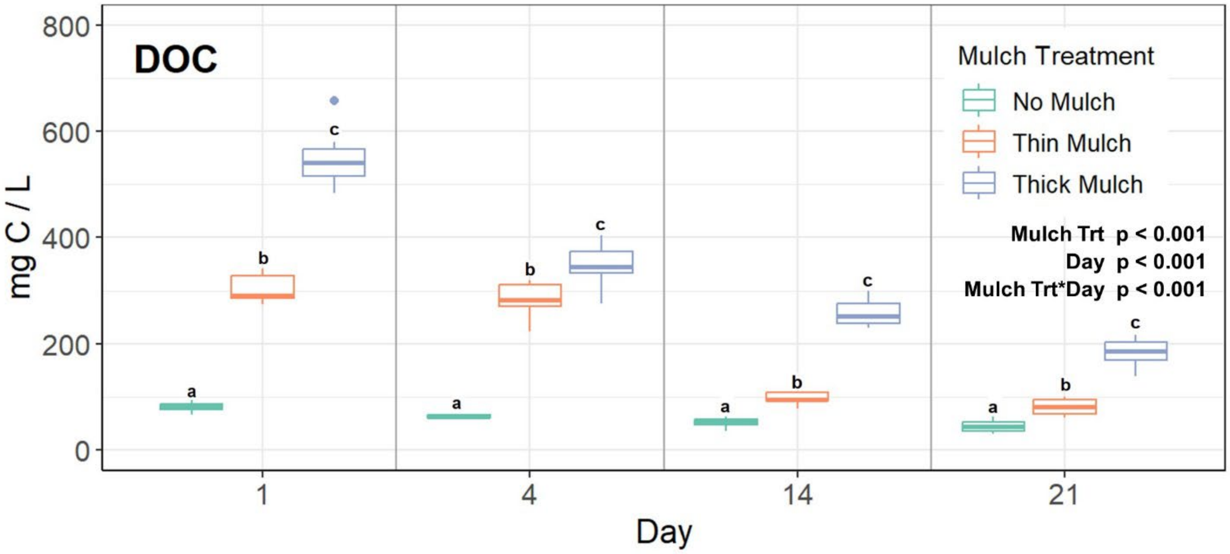


Figure 4. Leachate dissolved organic carbon generated by simulated rain events. The thin (1 cm) and thick (5 cm) mulch treatments added 8 and 37 Mg C ha^{-1}, respectively. The centerline of the boxplots denotes median, the upper and lower limits span the interquartile range, the whiskers include data within 1.5-times the interquartile range, 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 post-hoc comparisons with Tukey Bonferroni adjustments, following a two-way mixed ANOVA, at $\alpha = 0.05$ level.

The mulch treatments reduced nitrate losses compared to unmulched burned soils throughout the simulated rainfall trial and were influenced by the rain event (Figure 5). Averaged for the consecutive rain events, nitrate leached from the thin and thick mulch treatments was 22 and 27% lower than the unmulched treatment. Nitrate was mobilized quickly, and concentrations declined substantially after the second rain event. Nonetheless, mulched soils released significantly lower concentrations of nitrate than unmulched soils during the last two rain events. The impact of mulch on TDN was inconsistent, but temporal patterns were similar to those measured for nitrate.

Mulch influenced the proportion of TDN comprised by nitrate over the course of the consecutive rain events. In the first simulated storm event, leachate nitrate proportions of TDN were comparable across treatments and averaged 33%. By the last leaching, this proportion declined to 9% for the thick mulch treatment compared to 22% for the unmulched soils. However, the nitrate proportion of TDN for the thin mulch treatment did not decline and remained at 33% by the last rain event. Dissolved inorganic nitrogen (DIN) (NO_3-N + NH_4-N) in leachate was dominated by nitrate across all treatments. On average, in the first leaching nitrate made up 98% of the leached DIN and reduced to 90% by the last leaching event.

Over the consecutive leaching events, C:N in the leachate was higher in the mulched treatments compared to the unmulched treatment. In the first simulated rain storm, leachate C:N was 4 and 7-times greater in the thin and thick mulch treatments than the unmulched soil. For the thick mulch treatment, C:N was 6 in the first leaching event and increased to 64 by the end of the experiment. Comparatively, for the unmulched treatment, C:N was <1.0 in the first rain event and increased to 18 by the end of the trial.

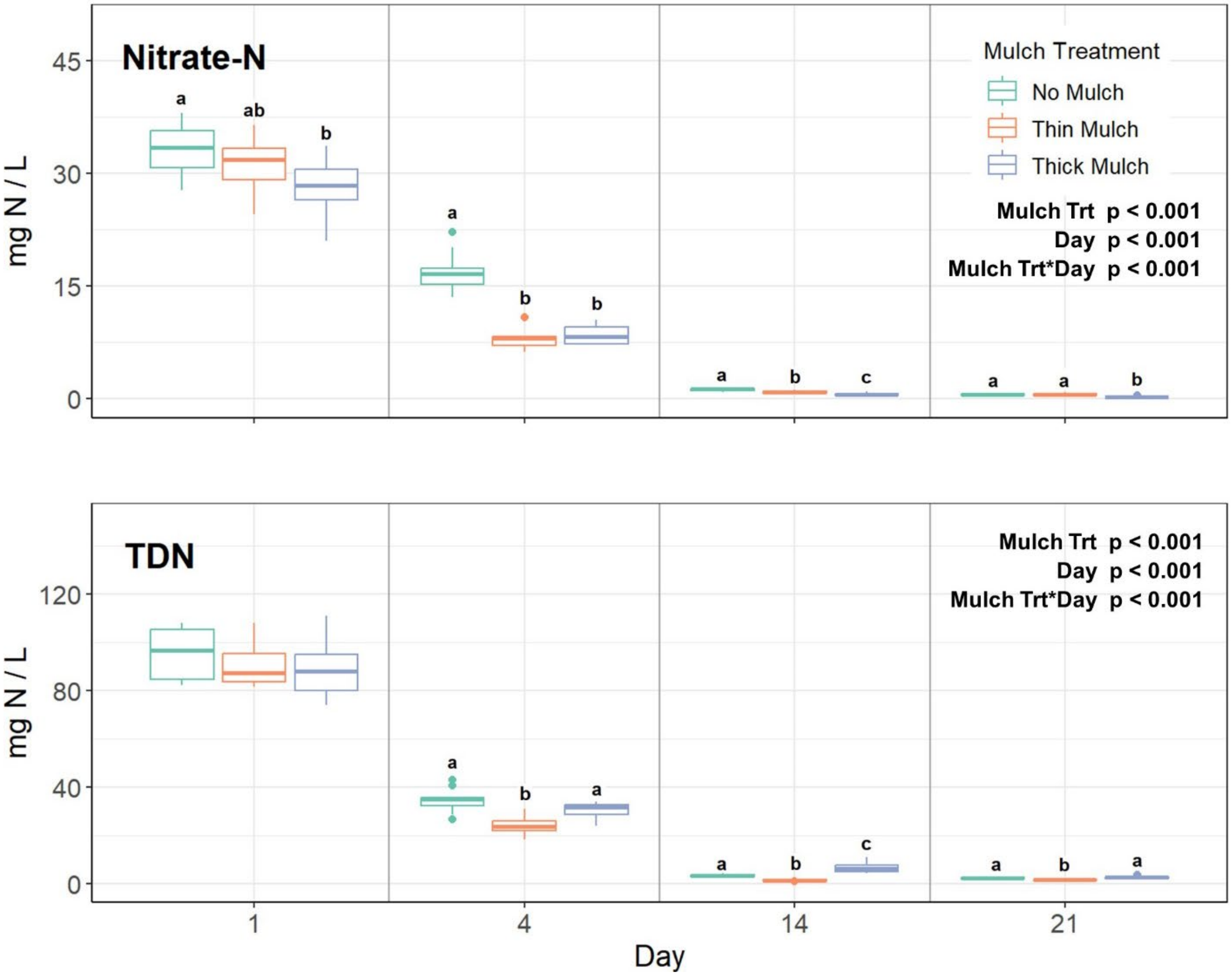


Figure 5. Leachate nitrate and total dissolved nitrogen (TDN) generated by simulated rain events. The centerline of the boxplots denotes median, the upper and lower limits span the interquartile range, the whiskers include data within 1.5-times the interquartile range, and the dots beyond the whiskers are outliers. Letters denote significant differences between treatment means (n = 10 replicates per treatment) within a rain event, according to post-hoc comparisons with Tukey Bonferroni adjustments, following a two-way mixed ANOVA, at α = 0.05 level.

3.2 Fire Effects on Hillslope-Scale Soil C and N

Properties of soils collected at the hillslope plots prior to the 2022 supplemental mulching varied by burned versus unburned mineral soil and by depth (Table 3). KCl extractable inorganic N was 5-times greater in burned soils than unburned at 0-5 cm depths and 2-3 times greater at 5-15 cm depths. C:N ratios in burned soils were 50% lower than unburned mineral soil at 0-5 cm depths and 24% greater at 5 -15 cm depths. Net mineralization rates were lower in burned mineral soils at both depths compared to rates in the unburned mineral soil. Net nitrification was more variable but was higher in burned mineral soil at the shallower depth.

Table 3. Soil properties and net N incubations at the Cameron Peak fire, Colorado. Soil samples were collected at depths of 0-5 and 5-15 cm in burned and unburned hillslope plots prior to the 2022 mulch application.

	Burned Mineral Soil		**Unburned Mineral Soil**		**Organic Horizon**
	0-5 cm	**5-15 cm**	**0-5 cm**	**5-15 cm**	
NO_3-N (mg N kg^{-1})	9.13	2.91	1.82	0.80	--
NH_4-N (mg N kg^{-1})	11.4	2.53	2.41	1.46	--
Total C (g N kg^{-1})	25.3	13.6	29.1	14.8	400
Total N (g N kg^{-1})	1.01	0.60	0.55	0.81	13.3
C:N	25.0	22.7	52.9	18.3	30.1
Net mineralization (mg N kg^{-1} d^{-1})	-0.37	-0.06	-0.16	0.003	--
Net nitrification (mg N kg^{-1} d^{-1})	0.05	0.04	-0.06	0.06	--

3.3 Mulch Impacts on Hillslope-Scale Soil N Availability and Soil Moisture

Similar to the simulated rainfall study, hillslope-scale mulch treatments reduced soil nitrate and total inorganic N (NO_3-N + NH_4-N) measured with ion exchange resins and the proportion of total inorganic N comprised of nitrate (Figure 6). Across all treatments, total IER-N and nitrate were 2 to 4-times greater in the winter than the summer. Mulch reduced nitrate measured during the winter deployment period that captured snowmelt. The 2-application mulch plots had 38% less soil nitrate compared to unmulched plots during the winter/snowmelt period. The 1-application mulch was intermediate and had 16% less soil nitrate compared to unmulched plots during the winter deployment. Total IER-N was also reduced in the mulched plots, sharing similar patterns to those measured in IER nitrate. During snowmelt, nitrate comprised 80% of total IER-N in thick mulch plots compared to 85% of total IER-N in unmulched plots, and these proportions decreased in the summer deployment. Ammonium measured with IER bags did not differ between treatments and averaged 0.26 and 0.30 mg N bag^{-1} during the summer and winter seasons.

Compared to unburned soils, burned soils had three-times more nitrate measured with IER bags, regardless of the season (Figure 6). For the winter season, soil nitrate comprised 85% of total IER-N in unmulched burned soils and 74% of total IER-N in unburned soils (Figure 6). From the IER-N assays measured during the summer season, nitrate proportions of the total IER-N were reduced to 68% in unmulched burned soils and 48% in unburned soils. Inorganic N collected as IER-N was lower during the drier summer months, but the unmulched, burned soil remained 2-times higher than unburned soil. During the winter season, the treatments with no mulch and the higher application rate mulch treatment had 149% and 58% more nitrate than unburned soils (Figure 6). Thus, although mulch reduced soil nitrate, it was not reduced to levels measured in the unburned site.

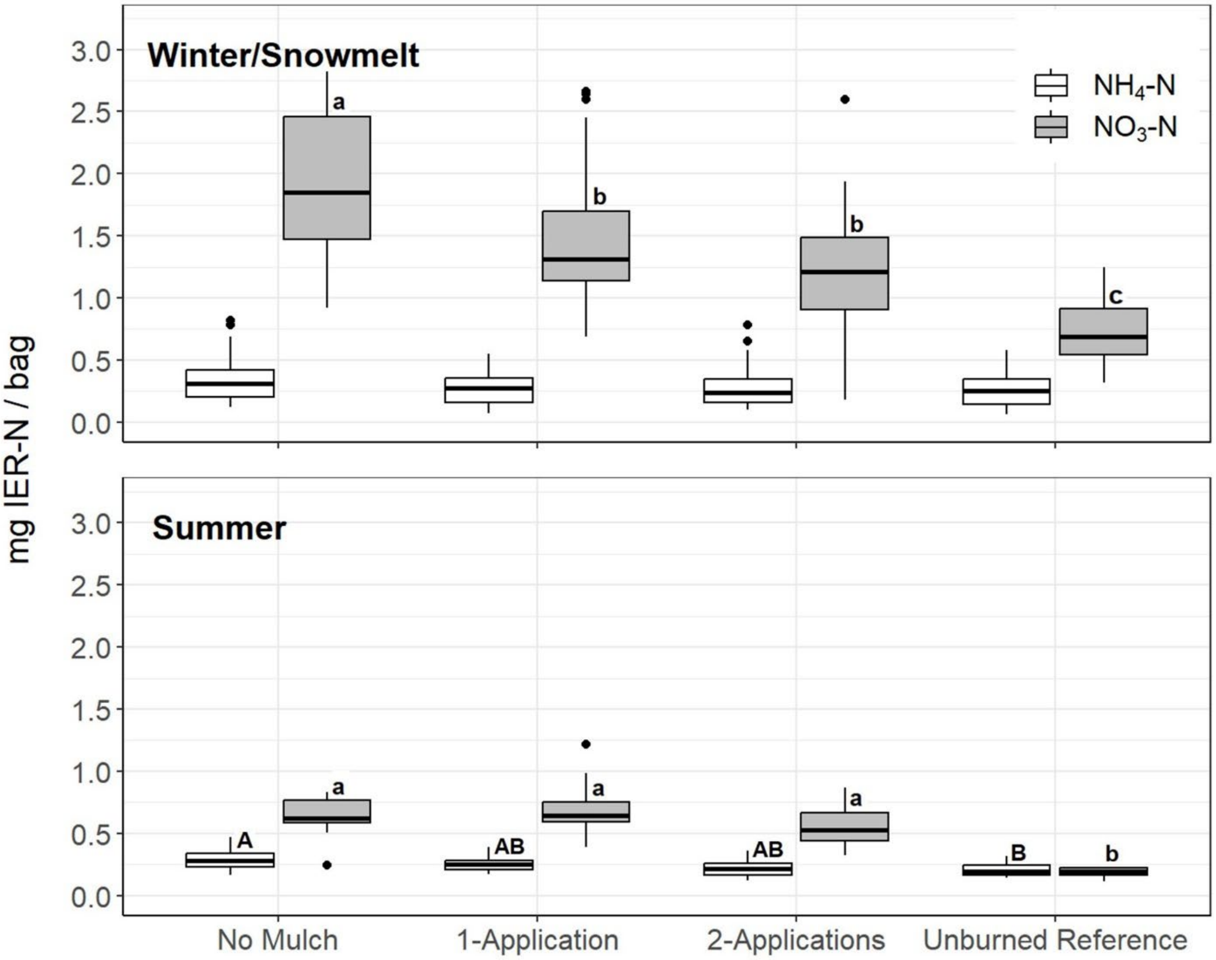


Figure 6. Soil nitrate (NO_3-N) and ammonium (NH_4-N) measured by ion exchange resin bags comparing hillslope treatments during winter/snowmelt (October – May) and summer (July – October) seasons. The centerline of the boxplots denotes median, the upper and lower limits span the interquartile range, the whiskers include data within 1.5-times the interquartile range, and the dots beyond the whiskers are outliers. Letters denote significant differences between treatment means (n = 12 plot replicates per treatment) for both total IER-nitrate (lowercase) and IER-ammonium (uppercase) using one way analysis of variance at $\alpha = 0.05$ level.

Wood mulch treatments did not have an evident effect on soil moisture in the hillslope plots (Figure 7, 8). Prior to the 2022 mulch application, there were more pronounced differences in the hillslope plots in early summer when the soil moisture was highest (7-12 %) (Figure 7). After the mulch application, soil moisture measurements were more similar between the plots. Regardless of the mulch treatment, soil moisture measurements were 2-times higher in the burned plots than the unburned plots. Soil moisture and IER nitrate-N were positively correlated for summer and winter measurements for all the treatments (Figure 9). These correlations were significant ($p < 0.05$) for all treatments except for the 2-applications mulch amendment, and the correlation was strongest ($R^2 = 0.75$) for the unburned forest. Mulch cover amongst the three treatments were categorized between high (>75%) and low (<25%) to better understand the influence on soil moisture (Figure 10). Hillslope plots with high mulch cover had significantly higher volumetric soil than those with low mulch cover. Although there were no significant differences of soil moisture means between treatments (Figure 8), hillslope plots with >75% mulch coverage had greater soil moisture than those with <25% mulch cover.

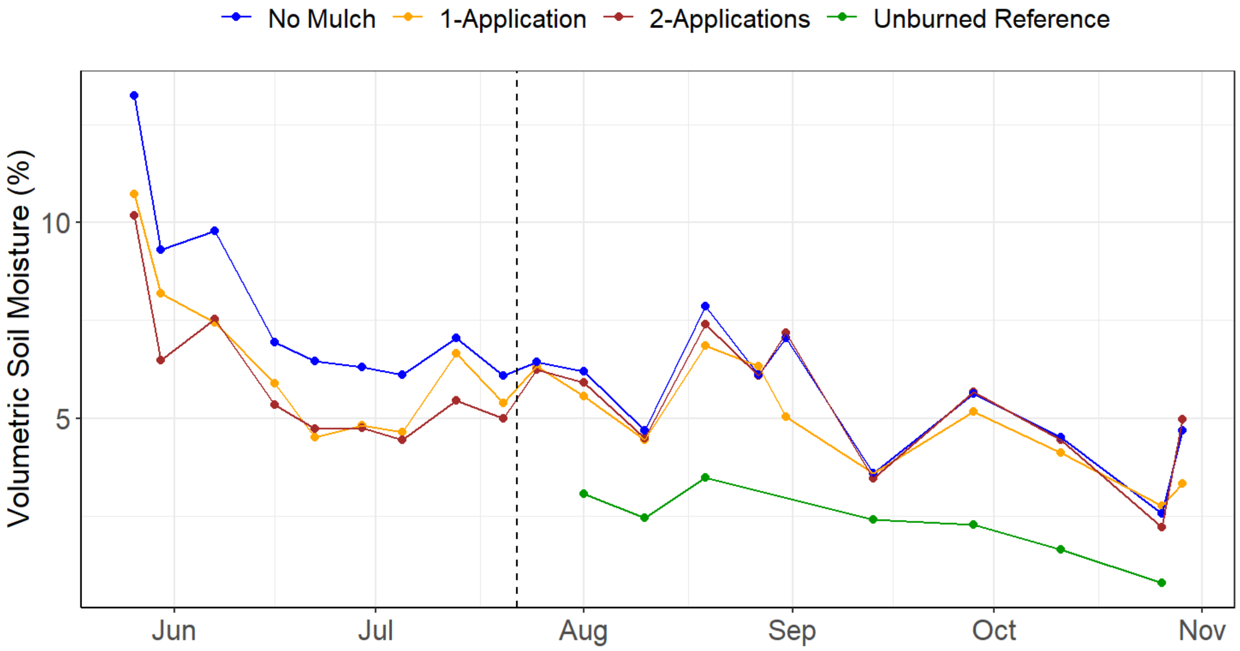


Figure 7. Volumetric soil moisture (10 cm depth) means in burned and unburned hillslope plots before (n = 8 plots per treatment) and after (n = 12 plots per treatment) supplemental mulching added in July 2022 (black dashed line). Prior to the 2022 mulch application, measurements were only taken at one of the hillslope sites, and then another site was established after. On average mulch cover was 6% prior to the additional mulching. After the supplemental additions, mulch cover averaged 6%, 36%, and 40% in the 'no' mulch, and 1 and 2-application treatments.

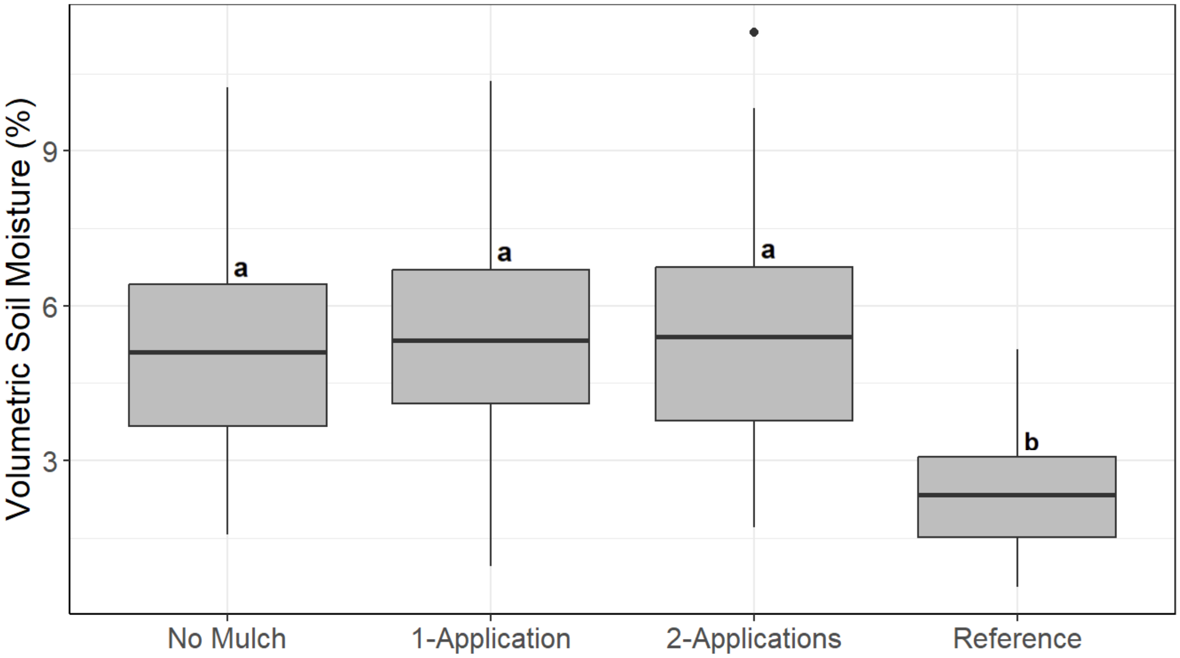


Figure 8. Soil moisture (0-10 cm depth) under post-wildfire mulch treatments after 2022 mulch application. Soil moisture was measured in hillslope plots per treatment weekly between July through October 2022 after the 2022 mulch application. The centerline of the boxplots denotes median, the upper and lower limits span the interquartile range, the whiskers include data within 1.5-times the interquartile range, and the dots beyond the whiskers are outliers. Letters denote significant differences among means (n = 12 replicate plots per treatment) at α = 0.05 level.

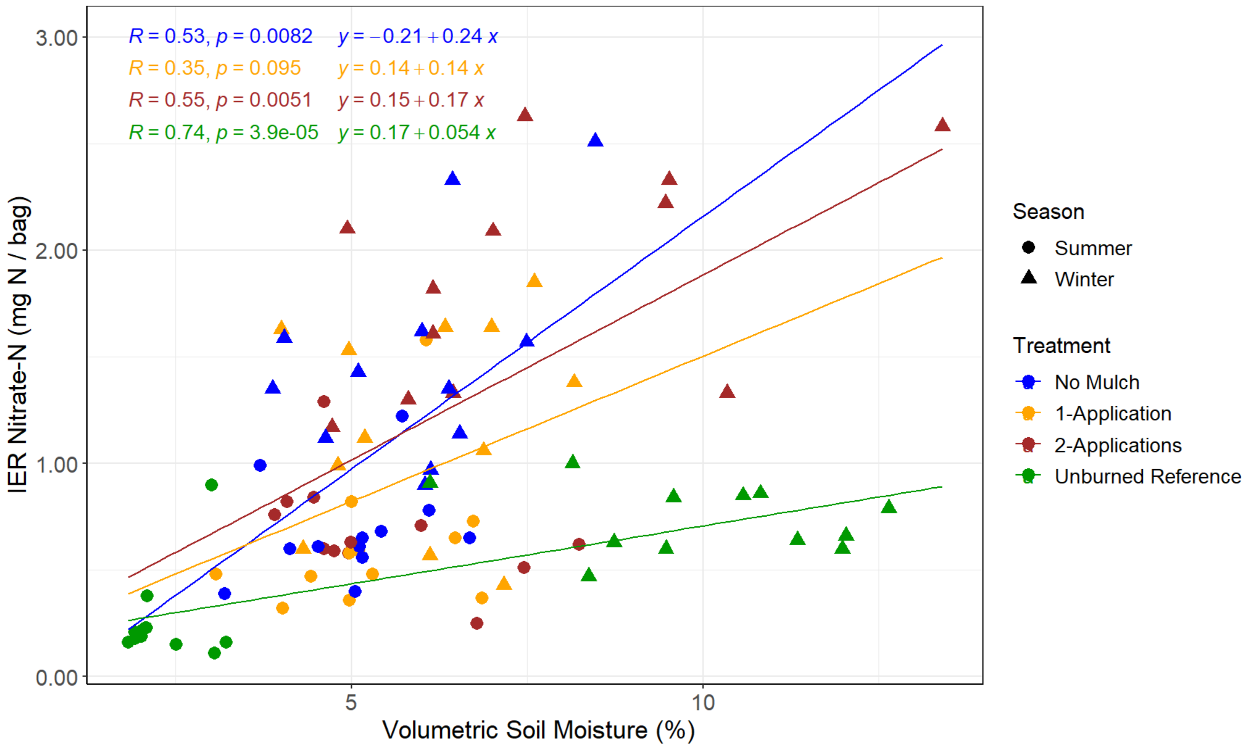


Figure 9. Relations between soil IER nitrate-N concentration and volumetric soil moisture means per individual plot comparing hillslope mulch treatments between summer and winter seasons in the Cameron Peak fire burn area. Each season had (n = 12 plot replicate plots per treatment) after supplemental mulch additions in 2022.

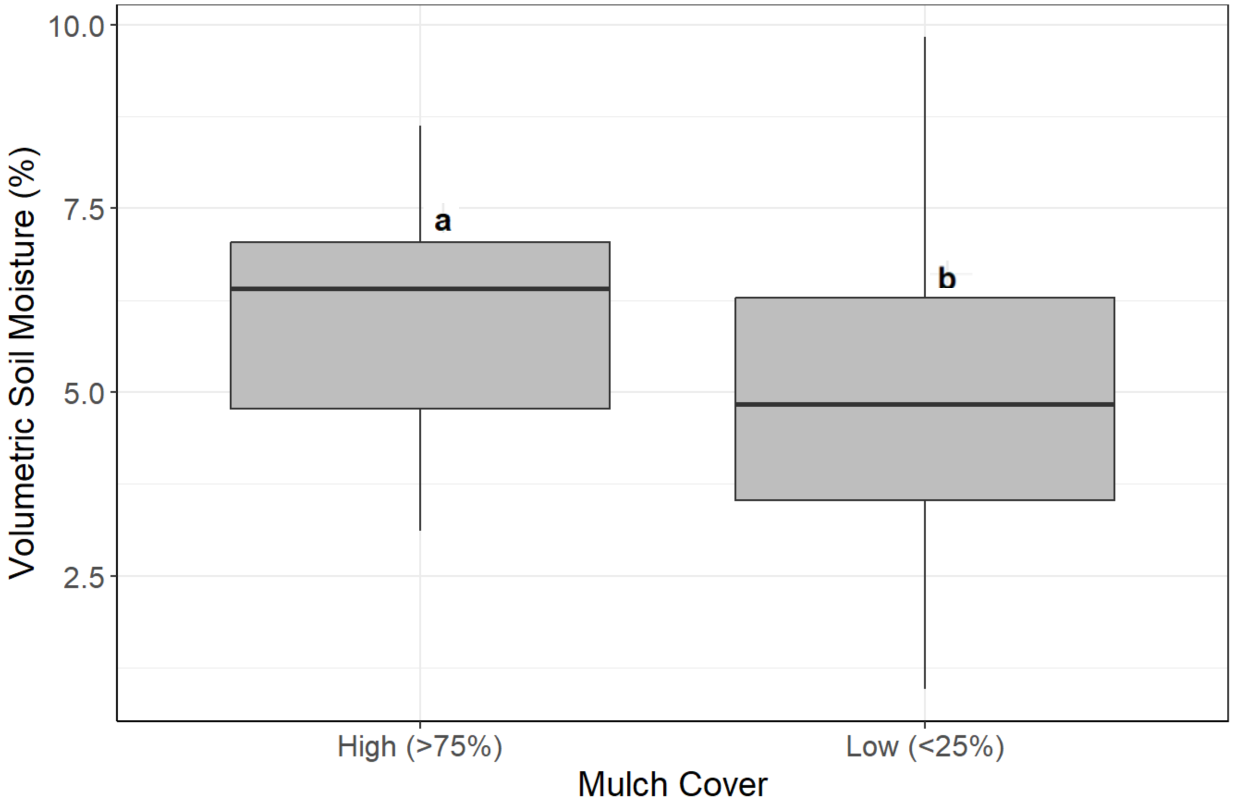


Figure 10. Volumetric soil moisture for high (>75%) and low (<25%) mulch cover in hillslope plots. Mulch cover was categorized amongst all three treatments (1. No mulch, 2. 1-application, 3. 2-applications). The centerline of the boxplots denotes median, the upper and lower limits span the interquartile range, the whiskers include data within 1.5-times the interquartile range, and the dots beyond the whiskers are outliers. Letters denote significant differences among means at α = 0.05 level.

3.4 Catchment Scale Mulching Consequences for Stream C and N

The high levels of carbon leached from the lab column studies due to mulch application were not detected in the study catchments. Dissolved organic carbon concentrations ranged between 3.2 – 8.8 mg C L^{-1} in the catchments (Table 4) compared to concentrations >100 mg C L^{-1} leached from the lab study (Figure 4). No significant differences in DOC concentrations were detected between mulched and unmulched catchments regardless of the season.

In contrast to the lab and plot-scale results, at the catchment scale, mulch did not have evident effects on stream nitrate concentrations. In the spring, mean nitrate concentrations ranged from 0.64 – 0.75 mg N L^{-1} in mulched catchments and 0.29 – 0.47 mg N L^{-1} in the unmulched catchments (Table 4). In the summer, mean nitrate concentrations ranged between 0.24 – 0.37 mg N L^{-1} in mulched catchments and 0.11 – 0.36 mg N L^{-1} in unmulched catchments. Nitrate proportions of TDN and DIN in both seasons were similar in mulched and unmulched catchments. Nitrate comprised 46% and 79% of TDN for spring and summer averaged across the catchments. In both mulched and unmulched catchments, nitrate comprised 94% and 79% of DIN for spring and summer seasons.

Table 4. Stream nitrate-N, total dissolved nitrogen, and dissolved organic carbon concentrations (mg L^{-1}) for Bennett Creek, Pennock Creek and the study catchments that were perennial for spring (April through mid-June) and summer (mid-June through August) seasons for 2022. Spring means have a sample size of 7 and summer has a sample size of 11. Significant differences for concentration means between the catchments are identified using non-parametric Kruskal-Willis test with a significance level of $\alpha = 0.05$. Letters denote significant differences between catchment means using Dunn Test, Holm-Bonferroni adjusted p-values.

Stream Chemistry	**Season**	**Bennett**	**Pennock**	**Mulch West**	**Mulch East**	**Unmulch West**	**Unmulch Middle**	*p*
NO_3-N (mg N L^{-1})	Spring	0.52^{a}	0.15^{b}	0.64^{a}	0.75^{a}	0.47^{ac}	0.29^{bc}	<0.001
	Summer	0.12^{ac}	0.04^{a}	0.24^{bc}	0.37^{b}	0.11^{ac}	0.26^{bc}	<0.001
	Annual Max	1.5	0.07	1.4	1.3	0.96	0.65	--
TDN (mg N L^{-1})	Spring	0.70^{a}	0.35^{a}	0.87^{ab}	1.0^{b}	0.66^{ab}	0.48^{a}	0.002
	Summer	0.46^{ab}	0.21^{a}	0.56^{ab}	0.72^{b}	0.28^{ab}	0.53^{a}	0.002
	Annual Max	1.6	0.95	1.5	1.5	1.1	0.95	--
DOC (mg C L^{-1})	Spring	6.2^{ab}	6.4^{ab}	7.5^{abc}	7.7^{ac}	5.9^{b}	8.8^{c}	<0.001
	Summer	4.7^{a}	3.7^{ab}	4.0^{ab}	4.5^{a}	3.8^{ab}	3.2^{b}	0.002
	Annual Max	6.7	6.4	8.2	8.4	6.1	9.8	--

Instantaneous concentrations of stream nitrate-N and DOC in the study catchments showed seasonal patterns and storm responses that were consistent between mulched and unmulched catchments (Figure 11). Across the study catchments, stream nitrate-N concentration means ranged from 0.11 – 0.75 mg N L^1 and nitrate proportions made up 39 – 75% of TDN. Both nitrate-N and TDN were elevated in the spring, then steadily declined into the summer months (Figure 11). Nitrate made up 64 - 96% of DIN across the study catchments, with lower values during the summer. These seasonal patterns were comparable to soil nitrogen measured at the hillslope scale (Figure 6). Dissolved organic carbon concentration means ranged between 3.2 – 8.8 mg L^{-1}, and increased during the spring snowmelt, then rapidly decreased moving into the summer season. Both C and N were responsive to summer storm events (Figure 11). Mulched catchments were most responsive with all N and C stream concentrations increasing by factors of 2-3 compared to non-storm samples.

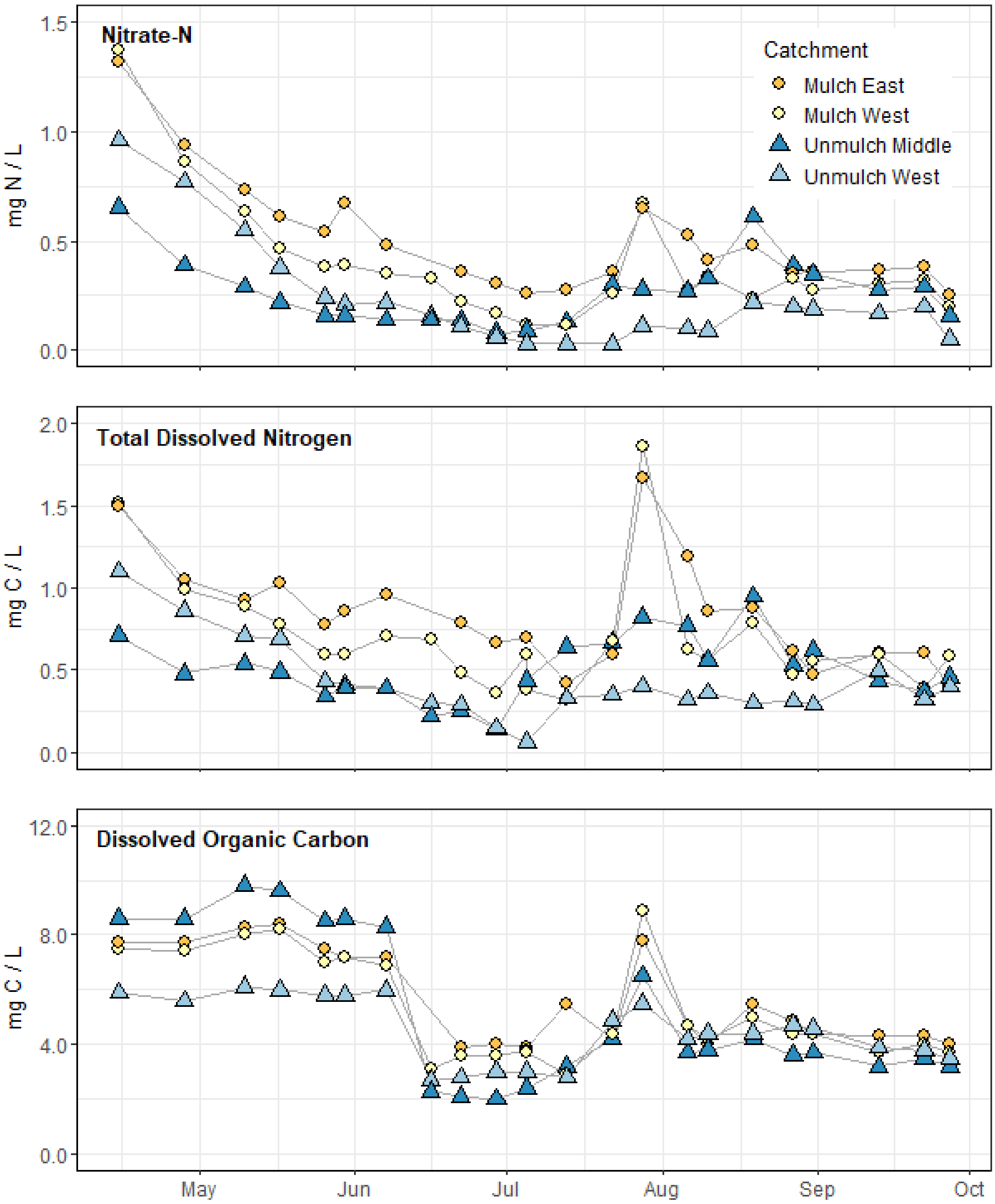


Figure 11. Instantaneous stream concentrations of nitrate-N, total dissolved nitrogen, and dissolved organic carbon for 2022 of the Bennett Creek study catchments that maintained perennial flow within the Cameron Peak fire, Colorado.

Bennett Creek, the larger burned watershed that the study catchments drain into, had higher average C and N concentrations than unburned, Pennock Creek across the seasons (Figure 12). Regardless of the mulch treatment, the study catchments had generally similar seasonal trends to Bennett Creek where both DOC and nitrate were generally highest in the spring and declined after the snowmelt peak. The nitrate proportions of TDN and DIN from the study catchments were generally more similar to those in Bennett Creek than to those in Pennock Creek. Across seasons, nitrate comprised 58% and 46% TDN for the study catchments and Bennett Creek compared to 31% for Pennock Creek. Similarly, nitrate proportions of DIN were 87% and 84% for the study catchments and Bennett Creek compared to 73% for Pennock Creek. Patterns of reduced nitrate proportions in the unburned stream are similar to those measured with IER bags in the unburned hillslope site (Figure 6).

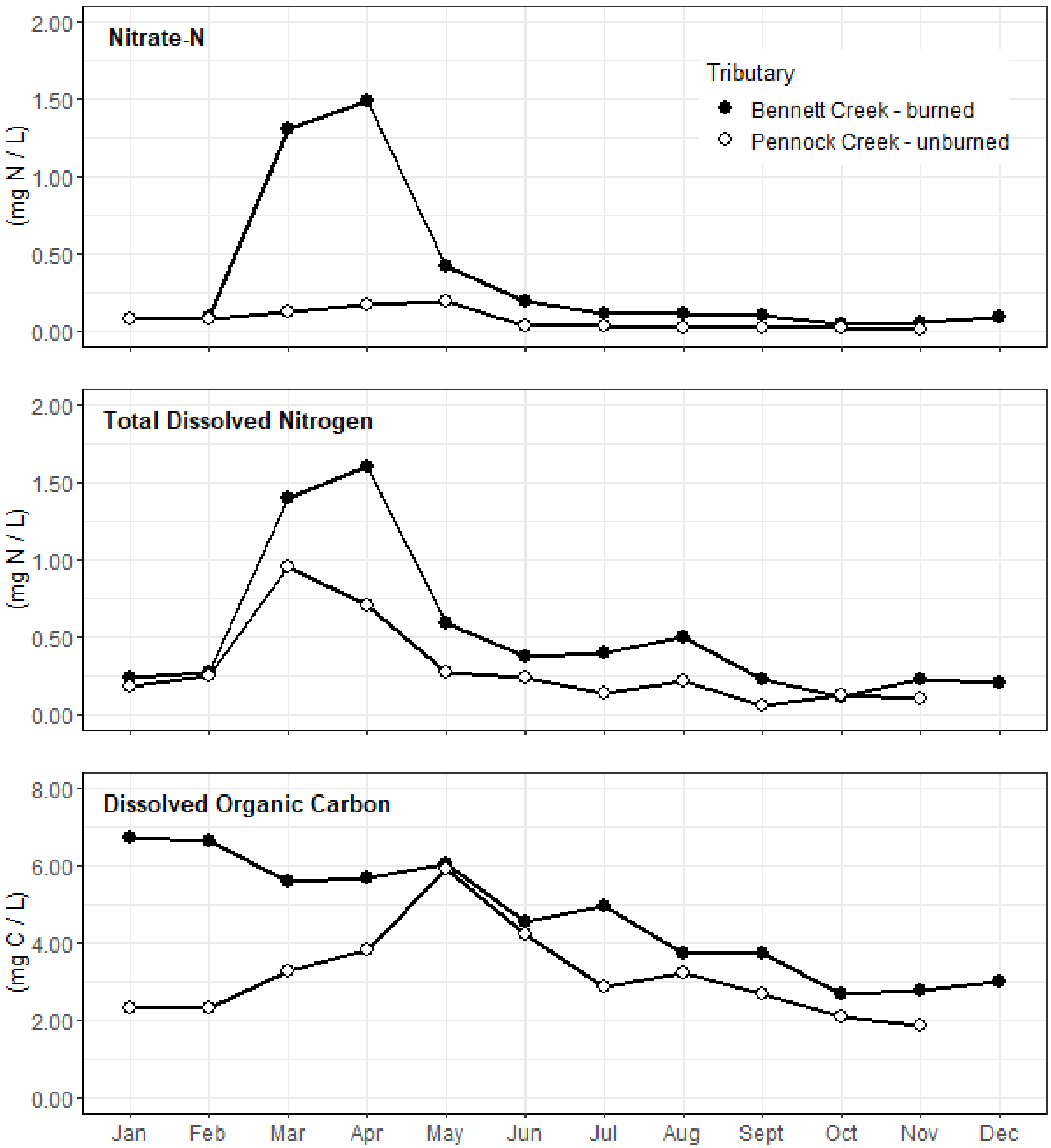


Figure 12. Monthly mean nitrate-N, TDN, and DOC concentrations in Bennett and Pennock Creeks in 2022.

Some of the topographic, fire, cover, and geomorphic metrics were similar for mulched and unmulched catchments, but unmulched catchments had greater proportions of high burn severity, smaller catchment areas, lower erosion, and lower valley fractions (Figure 13). Several catchment variables were positively correlated with one another, including slope and index of connectivity (r(6) = 0.92, p =0.01); slope and the bedrock fraction (r(6) = 0.87, p = 0.025), and erosion and valley fraction (r(6) = 0.88, p = 0.02). Predictor variable relationships with instantaneous dissolved organic carbon and nitrate-N concentrations shifted seasonally for the Bennett Creek catchments (Figure 14 and 15). In the spring, slope (r(6) = 0.83, p = 0.041) and connectivity (r(6) = 0.85, p = 0.033) were positively correlated with stream nitrate-N, whereas NDVI was negatively correlated (r(6) = -0.82, p = 0.048) (Figure 14). For stream DOC concentrations, only high burn severity was strongly positively correlated (r(6) = 0.90, p = 0.016) (Figure 14). In the summer, no catchment characteristics were strongly correlated with mean nitrate-N concentrations (Figure 15). Comparatively, connectivity (r(5) = 0.88, p = 0.047) and erosion (r(5) = 0.89, p = 0.045, were strongly positively correlated with summer DOC concentration means (Figure 15).

A closer look at some of these correlation patterns reveals seasonal shifts in relationships between predictors and N and C concentrations. Nitrate concentrations decreased with greater burn severity in both spring and summer, whereas DOC concentrations increased in spring, and decreased with greater burn severity in summer (Figure 16). Nitrate concentrations significantly increased with greater slopes in the spring but were not related to catchment slope in summer (Figure 157. In contrast, DOC was not significantly correlated with slope in either season. Nitrate generally increased with higher catchment erosion in both spring and summer, whereas DOC increased significantly with higher erosion only in summer (Figure 18).

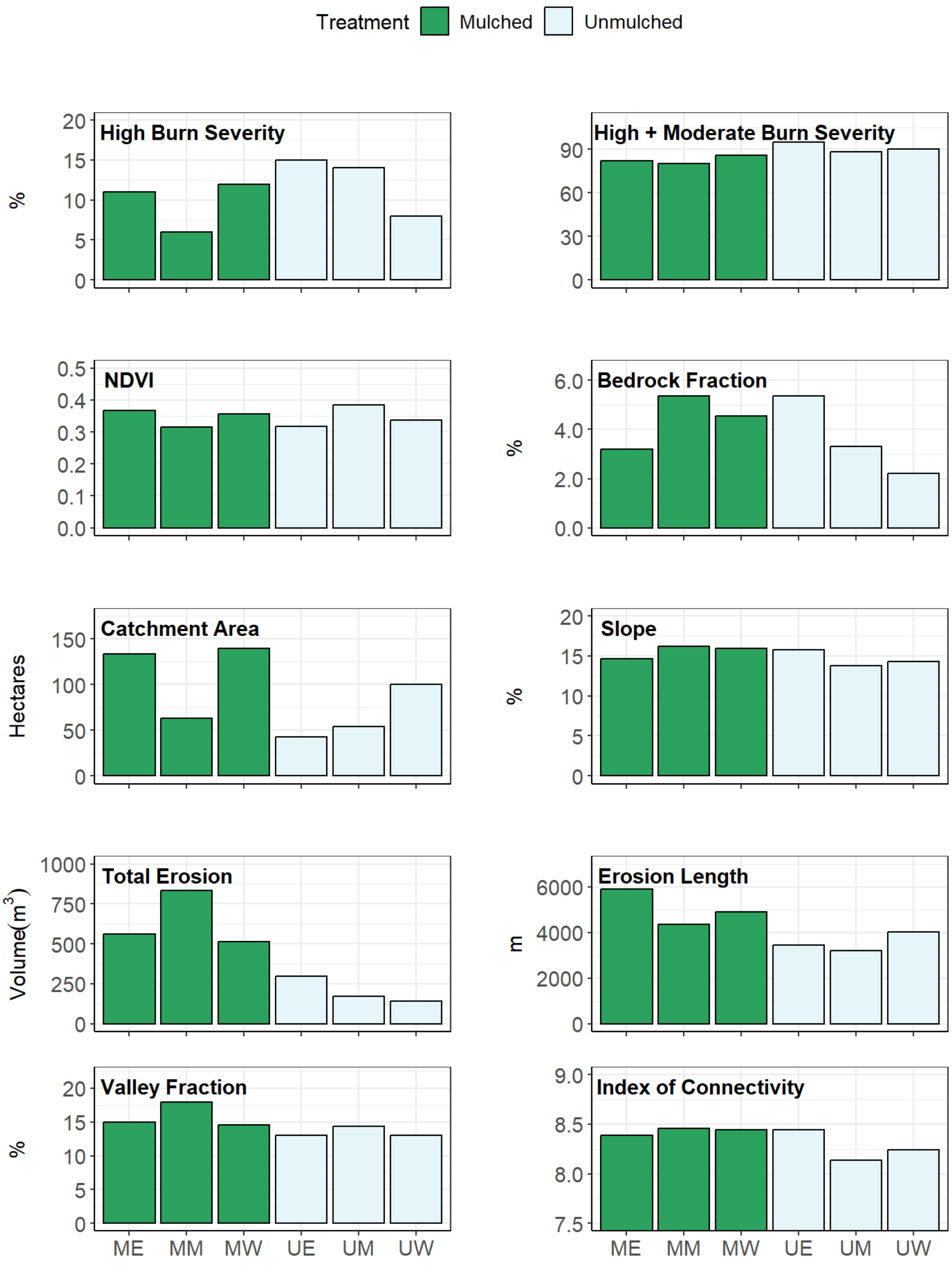
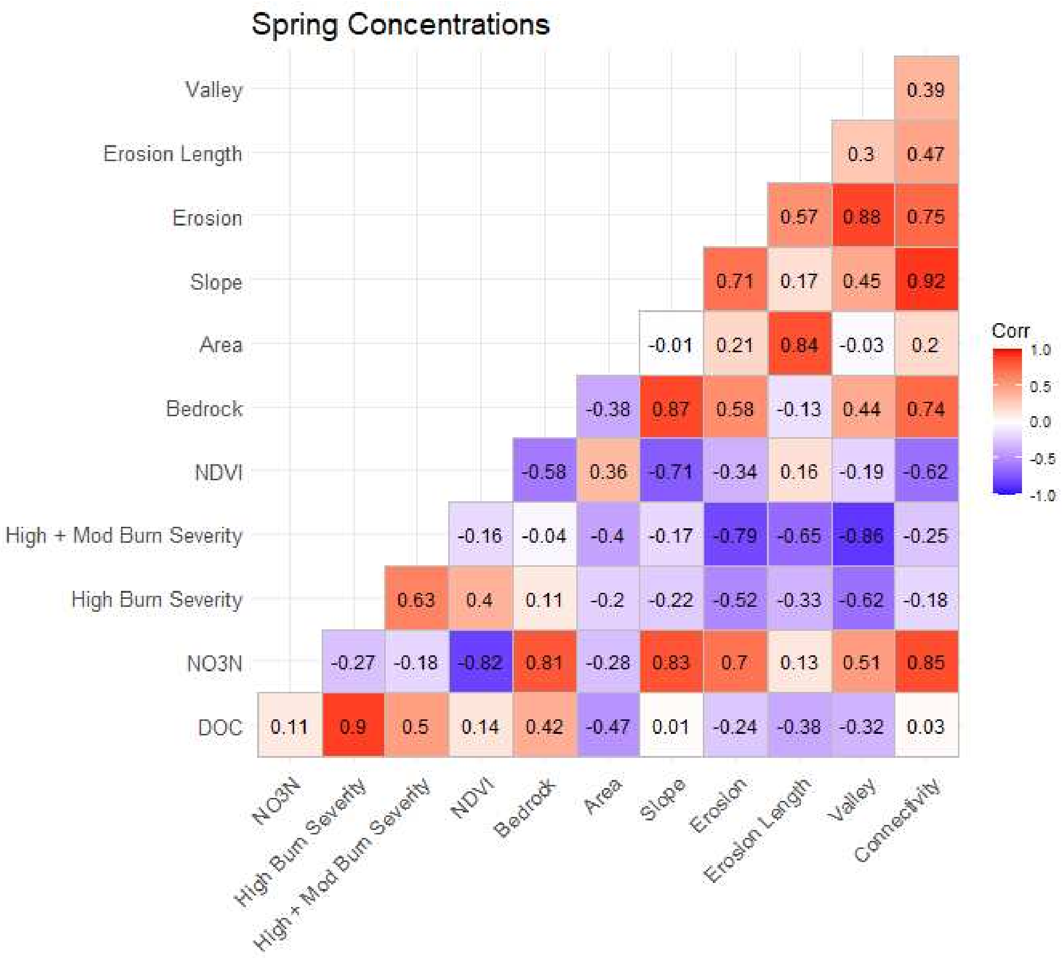


Figure 13. Watershed metrics for mulched and unmulched study catchments within the Bennett Creek watershed located in the Cameron Peak fire burn scar.



	NO3N	High Burn Severity	High + Mod Burn Severity	NDVI	Bedrock	Area	Slope	Erosion	Erosion Length	Valley	Connectivity
Valley											0.39
Erosion Length										0.3	0.47
Erosion									0.57	0.88	0.75
Slope								0.71	0.17	0.45	0.92
Area							-0.01	0.21	0.84	-0.03	0.2
Bedrock						-0.38	0.87	0.58	-0.13	0.44	0.74
NDVI					-0.58	0.36	-0.71	-0.34	0.16	-0.19	-0.62
High + Mod Burn Severity				-0.16	-0.04	-0.4	-0.17	-0.79	-0.65	-0.86	-0.25
High Burn Severity			0.63	0.4	0.11	-0.2	-0.22	-0.52	-0.33	-0.62	-0.18
NO3N		-0.27	-0.18	-0.82	0.81	-0.28	0.83	0.7	0.13	0.51	0.85
DOC	0.11	0.9	0.5	0.14	0.42	-0.47	0.01	-0.24	-0.38	-0.32	0.03

Figure 14. Pearson correlation matrix between predictor variables and NO_3-N and DOC concentrations for samples collected in spring (April through mid-June) 2022 in the Bennett Creek study catchments.

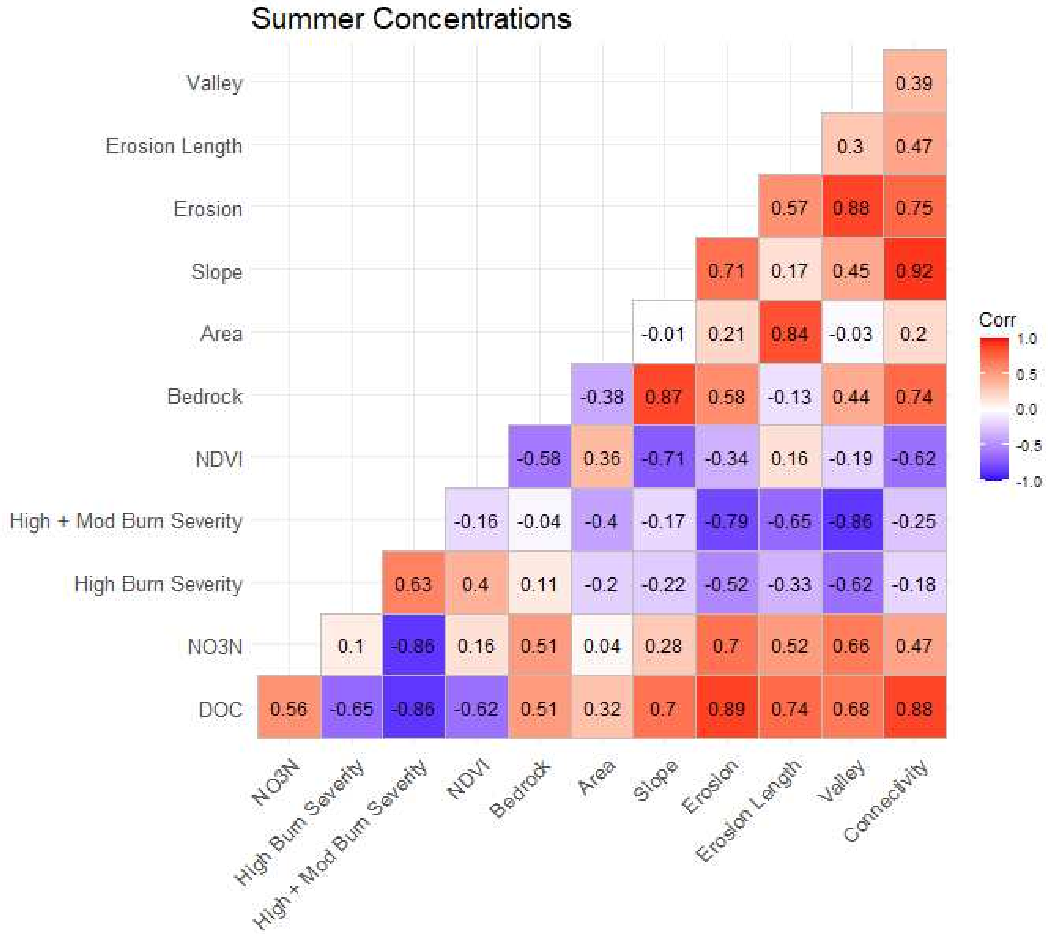


Figure 15. Pearson correlation matrix showing the relationship between predictor variables and NO_3-N and DOC concentrations for samples collected in summer (mid-June through August) 2022 in the Bennett Creek study catchments.

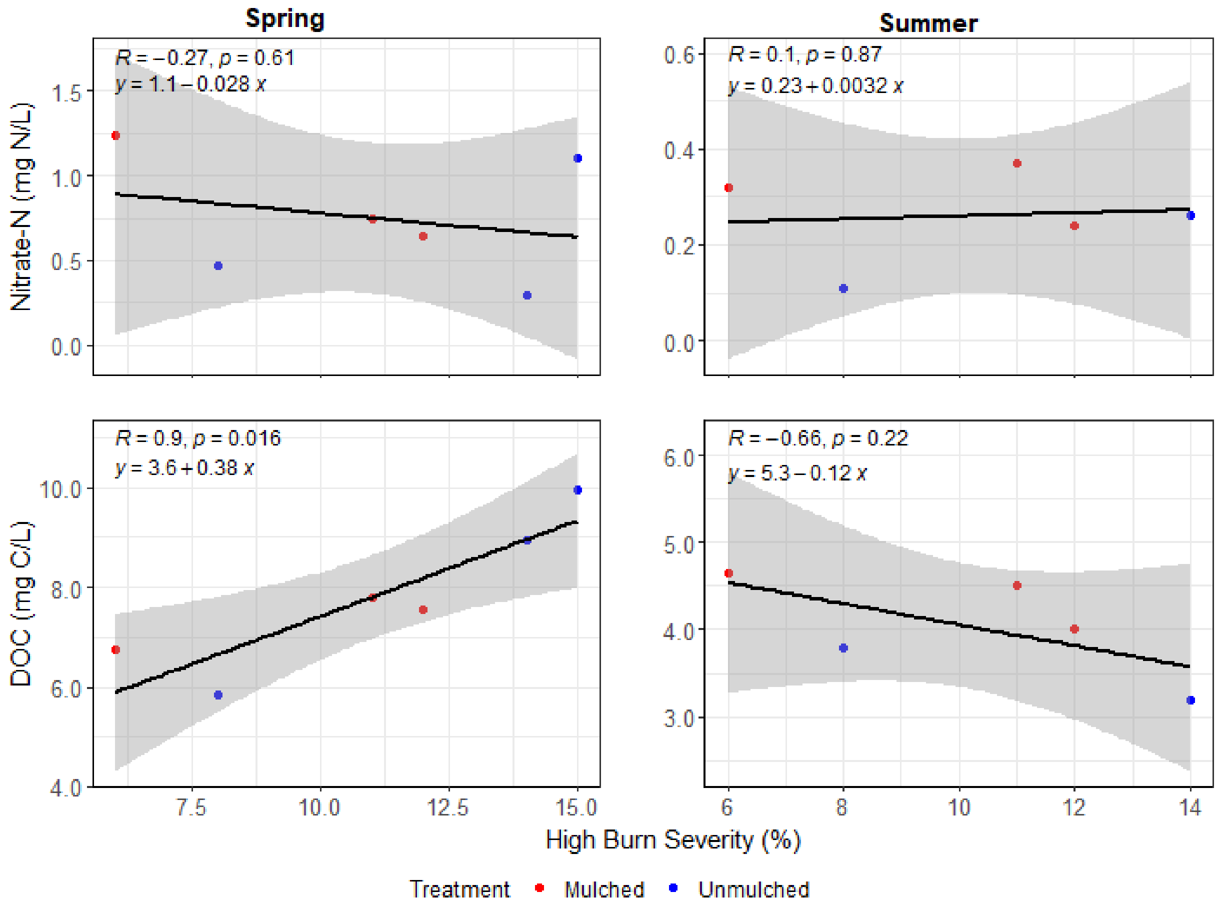


Figure 16. Relations between stream NO_3-N and DOC concentrations and high burn severity (%) of Bennett Creek study catchments for the spring (April through mid-June) and summer (mid-June through August) of 2022. The shaded region represents the confidence interval of 95%.

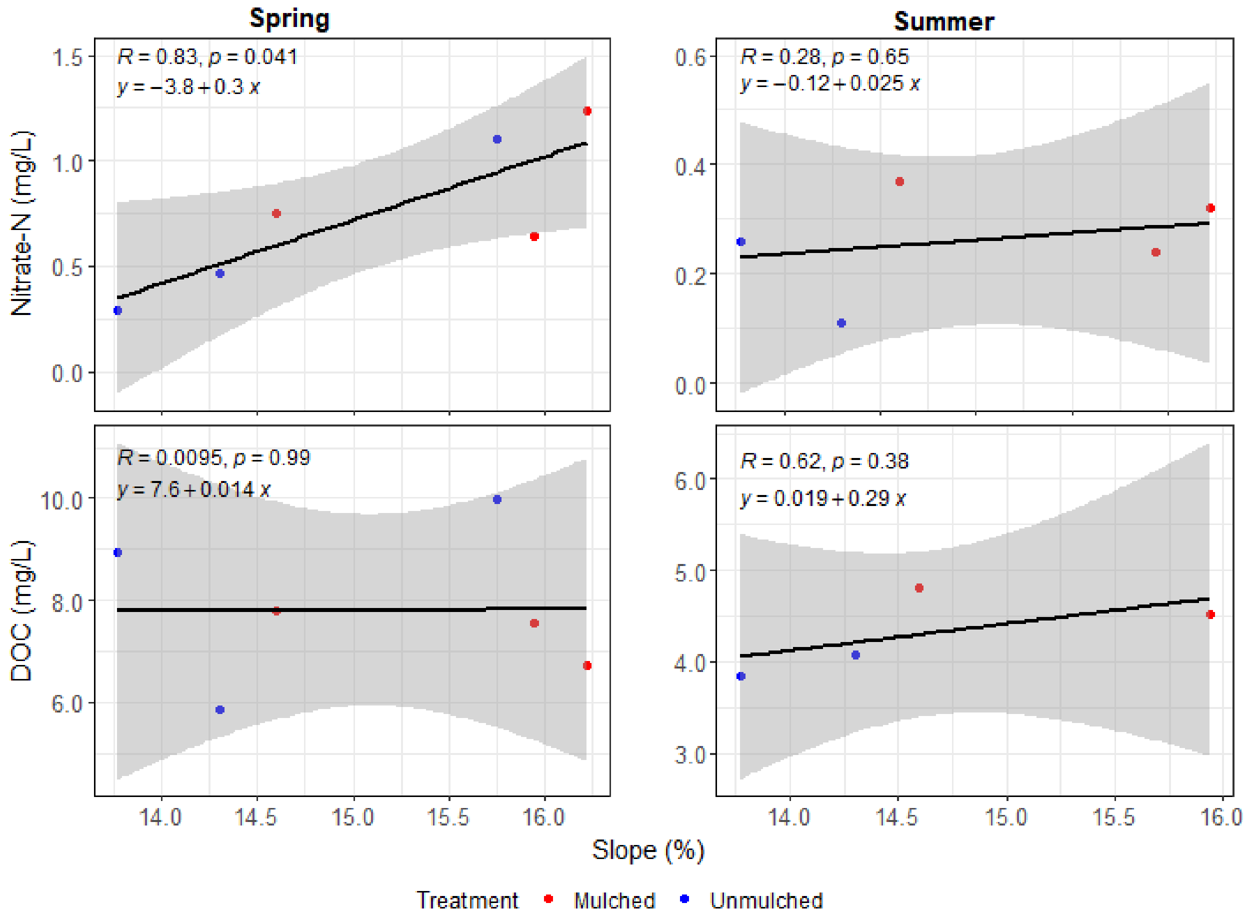


Figure 17. Relations between stream NO_3-N and DOC concentrations and average slope (%) of the Bennett Creek study catchments for the spring (April through mid-June) and summer (mid-June through August) of 2022. The shaded region represents the confidence interval of 95%.

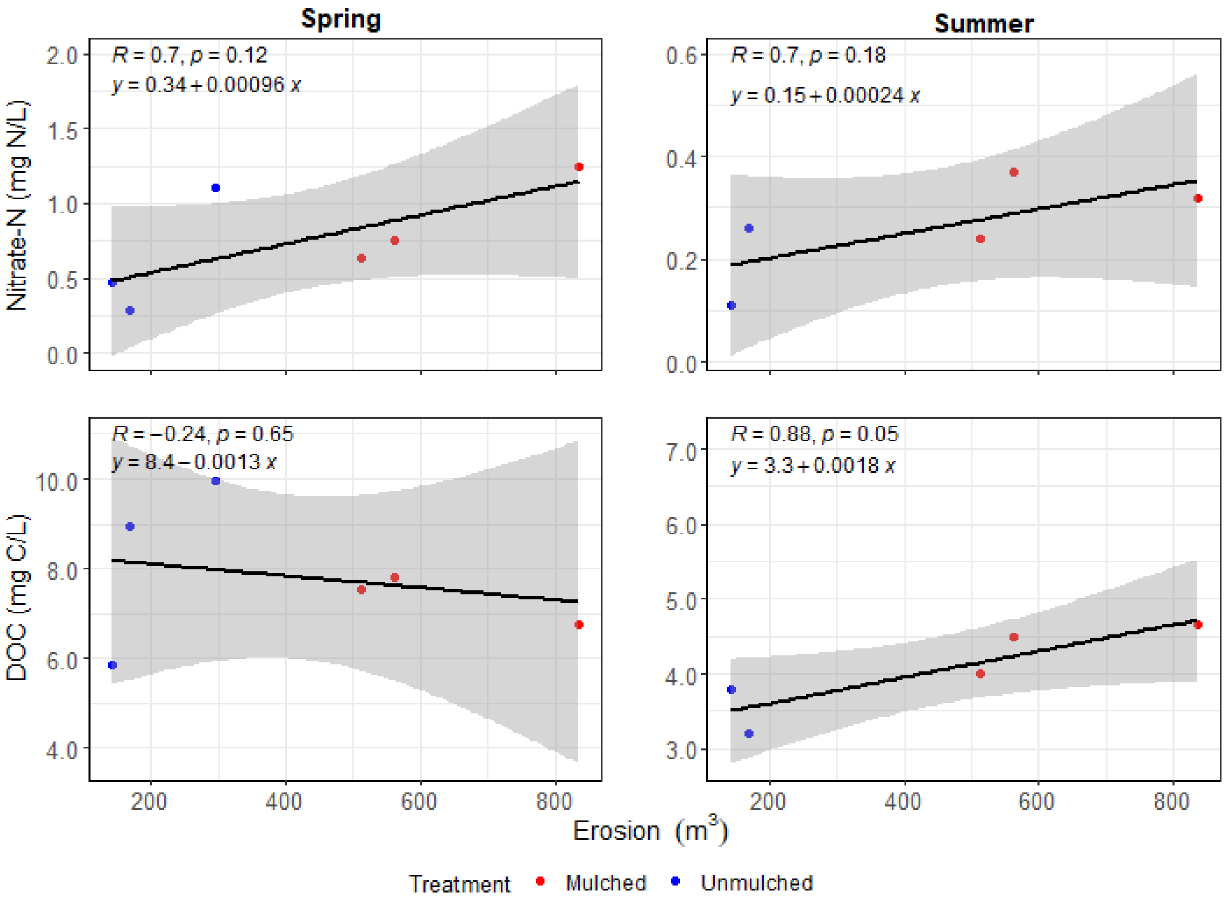


Figure 18. Relations between stream NO3-N and DOC concentrations and total volume of erosion in digitized pathways (m^3) of the Bennett Creek study catchments for the spring (April through mid-June) and summer (mid-June through August) of 2022. The shaded region represents the confidence interval of 95%.

4. DISCUSSION

4.1 Mulch-Related Carbon Inputs and Soil Leaching

Woody mulch adds considerable amounts of soluble C to soil that has the potential to alter soil N cycling. Labile C contained in DOC fuels microbial metabolism and can stimulate N immobilization (Uddin et al., 2020) and thus reducing inorganic N available for leaching losses from soils. Our thin mulch treatment, which approximated mulch depths measured at our field sites, released between 100 and 300 C L^{-1} of DOC during simulated rain events. Mulch leachate had a lower C:N ratio than solid mulch (i.e., 50 vs 110; Table 5), consistent with high substrate quality of the soluble C released from mulch. The series of simulated rain events mobilized 13 kg C ha^{-1} of DOC, which represented 0.2% of the total C contained in the solid mulch. It is unknown if the amount of soluble C is completely exhausted or if mulch will continue to release DOC as it decomposes. Previous studies document that DOC release from woodchips can persist for up to seven years (Abusallout and Hua, 2017; Pitman et al., 2021). Elevated and persistent post-fire DOC concentrations increase concerns associated with disinfection by-products (DBP) formation potential during drinking water treatment (Chow et al., 2019; Heath et al., 2016; Hohner et al., 2016). The potential benefits of mulching on post-fire N release would be limited if the treatment exacerbates concerns about elevated DOC and potential DBP formation.

Table 5. Total N and C in mulch (1 cm depth) and mineral soil (0-5 cm depth) and soluble N and C in mulch leachate used in laboratory column leaching study. Mulch leachate values are the cumulative input from mulch to soil columns during four consecutive simulated rain events.

	Total N (mg)	Total C (mg)	C:N
Mulch	13	1470	110
Mineral Soil	55	1250	23
Mulch Leachate	0.05	2.5	50

Although the laboratory studies measured substantial levels of leached C from mulched soils, the low mulch coverage in the field did not cause a detectable influence on stream DOC. On average, DOC concentrations from mulched catchments ranged between 4.0 to 7.7 mg C L^{-1} compared to 100 to 550 mg C L^{-1} leached from soil columns. Due to the low coverage, mulch mass was 16-times lower in the catchments compared to the laboratory soil columns. The total amount of soluble carbon from mulch added to the soil columns (13 kg C ha^{-1}) is comparable to the amount that would be added over the course of two summer months in the study area (NWS, 2024) and makes up 1.0% of the total carbon in mineral soil (Table 5). Thus, it does not enrich the soil with C compared to the amount of inert C that already exists in the soil. Additionally, the relative amount of DOC added to the soil is reduced by the greater spatial extent and low mulch coverage in the catchments. Therefore, the elevated DOC concentrations of concern for DBP formation in the leaching trials were not detectable in streams connected to mulched hillslopes.

We found that burned stream DOC concentrations were higher in the spring and comparable in the summer compared to unburned stream concentrations, two years after the Cameron Peak fire (Figure 12). Some studies have reported considerable increases of DOC concentrations after wildfire (Uzun et al., 2020), while others did not find a consistent trend (Mast et al., 2015; Santos et al., 2019). Typically, increases in DOC are found in the short term (1-2 years; Raoelison et al., 2023; Santos et al., 2019) due to initial flushes of recently generated ash during snowmelt or storm events (Mast et al., 2015; Uzun et al., 2020). However, this can be influenced by burn severity and topographic characteristics of the burned catchments. Post-fire increases of DOC concentrations can have detrimental effects on downstream water quality and cause complications for water treatment (Hohner et al., 2019; Uzun et al., 2020). Our findings indicate that mulch as a post-fire treatment does not increase levels of stream DOC that may already be elevated after wildfire.

We found that stream DOC variation in the study catchments was driven by topographic and geomorphic variability rather than the limited mulch application. DOC concentrations were elevated in the spring and increased during summer storm events. For our six catchments, all with relatively high and moderate burn severity, DOC concentrations were positively correlated with high burn severity in the spring (Figure 13). Other studies have shown DOC concentrations to be correlated with low burn severity, however, their research looked at impacts across a broader range of severities (Cheng et al., 2023; Chow et al., 2019; Santos et al., 2019). Higher temperature and volatilization of carbon in high intensity fires suggests they may lower export of organic carbon to streams (Hohner et al., 2019; Paul et al., 2022), which contrasts with our observations of increased DOC with greater burn severity. Another study found no relationship between DOC concentrations and burn extent and concluded that other watershed-specific factors and solubility restrictions were stronger controls on post-fire DOC concentrations (Barton et al., 2023). We also found that summer DOC concentration means increased with greater catchment erosion (Figure 17). This reflects the influence of summer storm events on DOC concentrations (Figure 10). Other studies have documented post-fire DOC increases during storm events (Murphy et al., 2022; Roebuck Jr. et al., 2022) due to fire altered soil surface conditions and increased overland flow (Doerr et al., 2000; Larsen et al., 2009). One study found linkages between turbidity and DOC, indicating that post-fire environments make it more available for transport through the dissolution and mobilization of particles through surface runoff during rain events (Roebuck Jr. et al., 2022).

4.2 Mulch Impacts on Post-Fire Soil and Stream Nitrate

We found that burned soils and surface water had higher nitrate levels and nitrate proportions of DIN compared to unburned sites, as has been reported widely (Certini, 2005; Gustine et al., 2022; Rust et al., 2018; Wan et al., 2001). We observed that mulch reduced nitrate relative to unmulched burned soils in both laboratory and hillslope comparisons, a pattern that is attributed to stimulation of microbial grown and N immobilization by C inputs from mulch (Prober et al., 2005; Uddin et al., 2020). This is consistent with several other studies that have found wood mulch reduces inorganic soil N that is susceptible to leaching (Homyak et al., 2008; Rhoades et al., 2015; Rhoades et al., 2017; Uwituze et al., 2023). However, during this short-term study soil nitrate measured on our mulched hillslopes did not decrease to levels observed in unburned soils. Though mulching is known to stimulate soil microbes and enhance soil enzyme activity that are depleted by fire (Carmona-Yañez et al., 2023; Holden et al., 2016; Ortega et al., 2023; Vourlitis et al., 2022), it can take years to return to pre-fire conditions (Ortega et al., 2023; Vourlitis et al., 2022). Post-fire recovery of soil microbial communities and activity can take up to 20 years (Fritze et al., 1993; Holden and Treseder, 2013; Caiafa et al., 2013), so by promoting microbial activity and N immobilization, mulching has the potential to speed recovery of the soil processes that retain N in soils rather than release to surface water.

Although our findings indicate that mulching can reduce inorganic soil N, it is uncertain how much of this transformation is caused by nitrogen immobilization into microbial biomass versus denitrification processes. In our leaching studies, the soils remained moist throughout the trial, keeping the pore space water filled 60% to avoid anaerobic conditions that favor denitrification. In the field, we did not measure denitrification, so it is not certain if it occurred. Increased organic C availability generally increases the denitrification process, therefore, resulting in the production of gaseous N losses, but this can also be dependent on limited oxygen when denitrifiers switch from aerobic to anaerobic respiration (Miller et al., 2012; Skiba, 2008). Typically, this is favored in areas where soil is saturated and oxygen is limited such as wetlands and riparian areas (Buss et al., 2005). Comparatively, our hillslope study sites had relatively well drained soils which might have reduced anaerobic conditions, but this was not measured. Additionally, one study has found that organic material with high C/N ratios could stimulate microbial immobilization of nitrate without causing concerning N loss via denitrification (Wang et al., 2021). Due to the potential for mulch to increase denitrification processes, it would be beneficial to quantify and further understand these unintended consequences associated with the input of C from mulch applications.

Our study indicated the largest mulch effect on soil nitrate during spring snowmelt when both nitrate and soil water content was highest, and hydrologic connectivity via subsurface flow paths between hillslopes and streams is greatest (Stieglitz et al., 2003; Stottlemeyer and Troendle, 1999). In the Rocky Mountains, N is generated by nitrification that continues beneath the snowpack throughout the winter (Brooks et al., 1998; Yano et al., 2019) and is released as a seasonal pulse during spring snowmelt (Mast et al., 2015; Rhoades et al., 2017; Rhoades et al., 2019). Nitrate release is typically elevated after wildfire (Table 4) due to decreased plant demand and higher nitrification rates (Table 3) (Certini, 2005; Gustine et al., 2022). We found that soil and stream nitrate were both 2 to 3-times greater during spring snowmelt compared to the summer season (Figure 6 and 9). During the summer, stream and soil nitrate declines as N uptake by terrestrial and aquatic biota increase (Campbell et al., 2002). The reduction in spring snowmelt soil nitrate we observed from the limited hillslope mulch application indicated that this treatment has the potential to impact N release to streams during this critical season.

Similar to stream DOC, we found that variability in stream nitrate in the study catchments was influenced by variation in topographic and geomorphic metrics rather than the limited mulch application. Steep topography promotes strong hydrologic gradients and coupling of burned hillslopes and streams through surface and subsurface flow paths (Lintern et al., 2018; Santos et al., 2019; Serpa et al., 2020). In our study catchments, stream nitrate concentrations in the spring increased with slope, connectivity, and total erosion, contributing to the observed snowmelt nitrate pulse. Similarly, other studies report that catchments with steeper slopes and greater hydrologic connectivity had elevated levels of post-fire N (Bladon et al., 2008). Despite selecting relatively similar catchments, the level of local catchment variability driving stream nitrate combined with the low mulch application limited our ability to detect any discernable mulch effect at the catchment scale. However, understanding catchment characteristics associated with increased post-fire stream nitrate may help to identify sensitive watersheds for focused mulch applications. Based on our findings, watersheds with high levels of hydrologic connectivity, steeper slopes, and evident erosion pathways would benefit from focused mulch applications. These attributes could be classified using high resolution airborne LiDAR and orthophotos.

Based on the low mulch coverage within the catchments (6%), there was no detectable signal on stream C and N. With other types of land cover change, often a lower percent area needs to be impacted before the effects are evident in streamflow; for example, studies of urban areas with impervious surfaces have detected impacts on water quality with impervious cover as low as 5-15% (Brabec et al., 2002; Schueler et al., 2009). In general, impervious surfaces provide more uniform cover change allowing for a clear link between impervious surface and hydrologic changes that influence water quality (Brabec et al., 2002), so likely more than 15%

mulch cover would be needed before a streamflow effect is evident. Additionally, research has established that a minimum mulch cover of 70% is required to provide effective post-fire erosion control (Girona-García et al., 2021; Robichaud et al., 2013). Without dense and consistent coverage, we would not expect to see considerable water quality changes from mulch applications.

Wildfires have long-term impacts on stream nitrate (Rhoades et al., 2019; Rust et al., 2019), though the potential persistent impacts of mulch treatments remain uncertain. We observed rapid depletion of soluble N during simulated rainfall events (Figure 5), consistent with the seasonal decline in leaching of soils and release to streams patterns. Though nitrate concentrations decreased with subsequent rain events, mulch impacts remained evident over the course of the trial. Elsewhere in Colorado, mulch applied in mechanical fuel reduction and pile burn rehabilitation projects reduced nitrate the first year after mulch application but did not persist the second year (Rhoades et al., 2012; Rhoades et al., 2015). In conjunction with redistribution of woody mulch, it is uncertain if the treatment will have lasting impacts within burned watersheds.

To extend the potential longevity of the wood mulch treatment, for both physical and biogeochemical influences, and prevent the movement of the material, mulch should be applied outside of the summer monsoon season. Similar to other studies (Foltz and Copeland, 2007; Robichaud et al., 2013), we found that mulch material was mobilized and redistributed within the first year of treatment. Wood mulch can interlock to create “mini-dams” which adsorbs rainfall impact and reduces the movement of the material (Girona-García et al., 2021); however, field observations have found when wood mulch cover is <50%, overland flow more easily displaces wood shreds (Robichaud et al., 2013). Therefore, by applying the mulch during a time that would limit movement during high intensity convective rainstorms, potentially early summer or fall depending on operational logistics, and with higher coverage, this could lengthen the longevity for the mulch treatment.

5. CONCLUSION

This evaluation of the biogeochemical effects of woody mulch advances understanding of the benefits but also the limitations of this treatment for post-fire water quality concerns. We document the potential for woody mulch to reduce post-fire nitrate leaching and inorganic soil nitrogen availability. However, the patterns we found in laboratory soil column assays 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 likely overwhelmed the ability to resolve catchment-scale C and N responses. The operational-scale application rate in this study was well below the minimum mulch cover recommended to treat post-fire erosion (i.e., 22% vs 70%: Girona-García et al., 2021; Robichaud et al., 2013). 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 experiment created a unique opportunity to evaluate the impacts of woody mulch at a relevant spatial scale, constraints associated with aerial operations prevented adequate mulching.

Given the considerable cost and operational limits associated with aerial mulch applications, treatments should prioritize sensitive and high value locations. Our findings demonstrate that adequately applied wood chip mulch can influence biogeochemical processes in burned watersheds. We also found that watersheds with greater hillslope connectivity and slopes had higher stream nitrate, particularly during spring snowmelt. Future research could further explore catchment characteristics associated with increased post-fire stream responses to help select candidate locations for focused mulch applications. Post-fire rehabilitation efforts aimed at protecting surface water quality should invest sufficient resources in prioritizing sensitive watershed locations and treating them with adequate mulch outside of the summer monsoon season to limit material redistribution during high intensity storm events and increase the longevity of the treatment. Little is known about the long-term biogeochemical impacts of post-fire mulching and the complementary role it can have on vegetation recovery. Land managers would benefit from research on these topics, along with work to pinpoint the parts of the watershed where mulching may have the greatest effect as well.

REFERENCES

Abusallout, I. and Hua, G. (2017). Characterization of dissolved organic carbon leached from a woodchip bioreactor. *Chemosphere, 183,* 36-43. https://doi.org/10.1016/j.chemosphere.2017.05.066

Andreu, V., Rubio, J.L., Forteza, J., and Cerni, R. (1996). Postfire Effects on Soil Properties and Nutrient Losses. *International Journal of Wildland Fire, 6*(2), 53-58. https://doi.org/10.1071/WF9960053

Averett, J.M., Klips, R.A., Nave, L.E., Frey, S.D., and Curtis, P.S. (2004). Effects of Soil Carbon Amendment on Nitrogen Availability and Plant Growth in an Experimental Tallgrass Prairie Restoration. *Restoration Ecology, 12*(4), 568-574. https://doi-org.ezproxy2.library.colostate.edu/10.1111/j.1061-2971.2004.00284.x

BAER (Burn Area Emergency Response). (2023). Soil Burn Severity Dataset for the CAMERON PEAK Fire occurring on the Arapaho & Roosevelt National Forests/Pawnee National Grassland National Forest. USDA Forest Service. https://burnseverity.cr.usgs.gov/baer/baer-imagery-support-data-download

Barton, R., Richardson, C., Pae, E., Montalvo, M., Redmond, M., Zimmer, M.A., and Wagner, S. (2023). Hydrology, rather than wildfire burn extent, determines post-fire organic and black carbon export from mountain rivers in central coastal California. *Limnology and Oceanography Letters, 9*(1), 70-80. http://dx.doi.org/10.1002/lol2.10360

Berryman, E.M., Morgan, M., Robichaud, P.R., and Page-Dumroese, D. (2014). Post-fire erosion control mulches alter belowground processes and nitrate reductase activity of a perennial forb, heartleaf arnica (*Arnica cordifolia*). USDA Forest Service – Research Note RMRS-RN (69). https://www.researchgate.net/publication/287341517_Post-fire_erosion_control_mulches_alter_belowground_processes_and_nitrate_reductase_activity_of_a_perennial_forb_heartleaf_arnica_Arnica_cordifolia

Binkley, D., and Matson, P. (1983). Ion Exchange Resin Bag Method for Assessing Forest Soil Nitrogen Availability. *Soil Science Society of America Journal, 47*(5), 1050-1052. https://doi.org/10.2136/sssaj1983.03615995004700050045x

Bladon, K.D., Silins, U., Wagner, M.J., Stone, M., Emelko, M., Mendoza, C., Devito, K., and Boon, S. (2008). Wildfire impacts on nitrogen concentration and production from headwater streams in southern Alberta's Rocky Mountains. *Canadian Journal of Forest Research, 38*(9), 2359-2371. http://dx.doi.org/10.1139/X08-071

Blumenthal, D.M., Jordan, N.R., and Russelle, M.P. (2003). Soil Carbon Addition Controls Weeds and Facilitates Prairie Restoration. *Ecological Applications, 13*(3). 605-615. https://doi.org/10.1890/1051-0761(2003)013[0605:SCACWA]2.0.CO;2

Borselli, L., Cassi, P., and Torri, D. (2008). Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment. *Catena, 75*(3), 268-277. http://dx.doi.org/10.1016/j.catena.2008.07.006

Brabec, E., Schutte, S., and Richards, P.L. (2002). Impervious Surfaces and Water Quality: A Review of Current Literature and Its Implications for Watershed Planning. *Journal of Planning Literature,* 499-514. https://doi.org/10.1177/088541202400903563

Brooks, P.D., Williams, M.W., and Schmidt, S.K. (1998). Inorganic nitrogen and microbial biomass dynamics before and during spring snowmelt. *Biogeochemistry, 43*(1), 1-15. https://doi-org.ezproxy2.library.colostate.edu/10.1023/A:1005947511910

Buss, S.R., Rivett, M.O., Morgan, P., and Bemmett, C.D. (2005). *Attenuation of nitrate in the sub-surface environment* (Science Report SC030155/SR2). Environment Agency. https://www.researchgate.net/publication/301518854_Attenuation_of_nitrate_in_the_sub-surface_environment

Caiafa, M.V., Nelson, A.R., Borch, T., Roth, H.K., Fegel, T.S., Rhoades, C.C., Wilkins, M.J., Glassman, S.I. (2023) Distinct fungal and bacterial responses to fire severity and soil depth across a ten-year wildfire chronosequence in beetle-killed lodgepole pine forests. *Forest Ecology and Management, 544*. https://doi-org.ezproxy2.library.colostate.edu/10.1016/j.foreco.2023.121160

Campbell, D.H., Kendall, C., Chang, C.C.Y., Silva, S.R., and Tonnessen, K.A. (2002). Pathways for nitrate release for an alpine watershed: Determination using δ^{15}N and δ^{18}O. *Water Resources Research, 38*(5), 101-109. https://doi.org/10.1029/2001WR000294

Carmona-Yañez, M.D., Francos, M., Miralles, I., Soria, R., Ahangarkolaee, S.S., Vafaie, E., Zema, D.A., and Lucas-Borja, M.E. (2023). Short-term impacts of wildfire and post-fire mulching on ecosystem multifunctionality in a semi-arid pine forest. *Forest Ecology and Management, 541*(1). https://doi-org.ezproxy2.library.colostate.edu/10.1016/j.foreco.2023.121000

Certini, G. (2005). Effects of fire on properties of forest soils: a review. *Oecologia, 143*(1). 1-10. http://www.jstor.org/stable/20062214

Cheng, Y., Luo, P., Yang, H., Li, H., Luo, C., Jia, H., and Huang, Y. (2023). Fire effects on soil carbon cycling pools in forest ecosystems: A global meta-analysis. *Science of The Total Environment, 895.* https://doi-org.ezproxy2.library.colostate.edu/10.1016/j.scitotenv.2023.165001

Chow, A.T., Tsai, K., Fegel, T.S., Pierson, D.N., and Rhoades, C.C. (2019). Lasting Effects of Wildfire on Disinfection By-Product Formation in Forest Catchments. *Journal of Environmental Quality, 48*(6), 1826-1834. https://doi-org.ezproxy2.library.colostate.edu/10.2134/jeq2019.04.0172

Coalition for the Poudre River Watershed. (2022). *Aerial Mulching – Cameron Peak Fire Burn Area*. https://www.poudrewatershed.org/aerial-mulching

Covington, W. W., DeBano, L. F., & Huntsberger, T. G. (1991). Soil nitrogen changes associated with slash pile burning in pinyon-juniper woodlands. *Forest Science*, *37*(1), 347-355. https://doi.org/10.1093/forestscience/37.1.347

Dennison, P.E., Brewer, S.C., Arnold, J.D., and Moritz, M.A. (2014). Large wildfire trends in the western United States, 1984-2011. *Geophysical Research Letters, 41*(8)*,* 2928-2933. https://doi.org/10.1002/2014GL059576

Dinno, A. (2017). -dunn.test: Dunn's Test of Multiple Comparison Using Rank Sums_. R package version 1.3.5, <https://CRAN.R-project.org/package=dunn.test>

Doerr, S.H., Shakesby, R.A., and Walsh, R.P.D. (2000). Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth-Science Reviews, 51*(1-4), 33-65. https://doi-org.ezproxy2.library.colostate.edu/10.1016/S0012-8252(00)00011-8

Dove, N.C., Safford, H.D. Bohlman, G.N., Estes, B.L., and Hart, S.C. (2020). High-severity wildlife leads to multi-decadal impacts on soil biogeochemistry in mixed-conifer forests. *Ecological Applications, 30*(4). https://doi-org.ezproxy2.library.colostate.edu/10.1002/eap.2072

Foltz, R.B., and Copeland, N.S. (2007). Field Testing of Wood-based Biomass Erosion Control Materials on Obliterated Roads. Paper No: 078046. Presented at: Annual International Meeting; 2007 June 17-20; Minneapolis, MN. St. Joseph, MI: American Society of Agricultural and Biological Engineers (ASABE). http://dx.doi.org/10.13031/2013.22965

Fritze, H., Pennanen, T., and Pietikainen, J. (1993). Recovery of soil microbial biomass and activity from prescribed burning. *Canadian Journal of Forest Research, 23*(7), 1286-1290. http://dx.doi.org/10.1139/x93-164

Girona-García, A., Cretella, C., Fernández, C., Robishaud, P.R., Vieira, D.C.S., and Keizer, J.J. (2023). How much does it cost to mitigate soil erosion after wildfires? *Journal of Environmental Management, 334.* https://doi-org.ezproxy2.library.colostate.edu/10.1016/j.jenvman.2023.117478

Girona-García, A., Vieira, D.C.S., Silva, J., Fernández, C., Robichaud, P.R., and Keizer, J.J. (2021). Effectiveness of post-fire soil erosion mitigation treatments: A systemic review and meta-analysis. *Earth-Science Reviews, 217.* https://doi-org.ezproxy2.library.colostate.edu/10.1016/j.earscirev.2021.103611

Gustine, R.N., Hanan., E.J., Robichaud, P.R., and Elliot, W.J. (2022). From burned slopes to streams: how wildfire affects nitrogen cycling and retention in forests and fire-prone watersheds. *Biogeochemistry, 157,* 51-68. https://doi-org.ezproxy2.library.colostate.edu/10.1007/s10533-021-00861-0

Harvey, B.J. (2016). Human-caused climate change is now a key driver of forest fire activity in the western United States. *Earth, Atmospheric, and Planetary Sciences, 113*(42). 11649-11650. https://doi.org/10.1073/pnas.1612926113

Hayter, L. (2023). *Evaluating Post-Fire Geomorphic Change on Paired Mulched and Unmulched Catchments Using Repeat Drone Surveys* [Master's Thesis, Colorado State University]. Mountain Scholar Digital Collection of Colorado. https://hdl.handle.net/10217/236836

Heath, J., Thorp, R., and Hill, L. (2016). *2015 Annual Report Upper Cache la Poudre Watershed Collaborative Water Quality Monitoring Program.* City of Fort Collins Utilities, Water Quality Services Division. https://www.fcgov.com/utilities/img/site_specific/uploads/2015_Annual_Report_1.pdf

Hohner, A.K., Cawley, K., Oropeza, J., Summers, R.S., and Rosario-Ortiz, F.L. (2016). Drinking water treatment response following a Colorado wildfire. *Water Research, 105*, 187-198. https://doi-org.ezproxy2.library.colostate.edu/10.1016/j.watres.2016.08.034

Hohner, A.K., Rhoades, C.C., Wilkerson, P., and Rosario-Ortiz, F.L. (2019). Wildfires Alter Forest Watersheds and Threaten Drinking Water Quality. *Accounts of Chemical Research, 52*, 1234-1244. https://doi/10.1021/acs.accounts.8b00670

Holden, S.R., Rogers, B.M., Treseder, K.K., and Randerson, J.T. (2016). Fire severity influences the response of soil microbes to a boreal forest fire. *Environmental Research Letters, 11,* 1-10. http://dx.doi.org/10.1088/1748-9326/11/3/035004

Holden, S.R. and Treseder, K.K. (2013). A meta-analysis of soil microbial biomass responses to forest disturbances. *Frontiers in Microbiology, 4*(163). https://doi.org/10.3389/fmicb.2013.00163

Homyak, P.M., Yanai, R.D., Burns, D.A., Briggs, R.D., and Germain, R.H. (2008). Nitrogen immobilization by wood-chip application: Protecting water quality in a northern hardwood forest. *Forest Ecology and Management, 255*(7), 2589-2601. https://doi.org/10.1016/j.foreco.2008.01.018

Jasiewicz, J., and Stepinski, T.F. (2013). Geomorphons – a pattern recognition approach to classification and mapping of landforms. *Geomorphology, 182*, 147 – 156. doi:10.1016/j.geomorph.2012.11.005

Jonas, J.L., Berryman, E., Wolk, B., Morgan, P., and Robichaud, P.R. (2019). Post-fire wood mulch for reducing erosion potential increases tree seedlings with few impacts on understory plants and soil nitrogen. *Forest Ecology and Management, 453*. https://doi-org.ezproxy2.library.colostate.edu/10.1016/j.foreco.2019.117567

Jones, M. W., Abatzoglou, J.T., Veraverbeke, S., Andela, N., Lasslop, G., Forkel, M., Smith, A.J.P, Burton, C., Betts, R.A., van der Werf, G.R., Sitch, S., Canadell, J.G., Santín, C., Kolden, C., Doerr, S.H., and Quéré, C.L. (2022). Global and Regional Trends and Drivers of Fire Under Climate Change. *Review of Geophysics, 60*(3). https://doi.org/10.1029/2020RG000726

Kurth, V. J., Hart, S. C., Ross, C. S., Kaye, J. P., & Fulé, P. Z. (2014). Stand-replacing wildfires increase nitrification for decades in southwestern ponderosa pine forests. *Oecologia, 175*(1), 395–407. https://doi.org/10.1007/s00442-014-2906-x

Lamm, J., Bastow, J., Brown, R., Nezat, C., and Lamm, A. (2021). Short-term nutrient reduction reduces cover of an invasive winter annual grass without negatively impacting the soil microbial community. *Restoration Ecology, 30*(1). https://doi-org.ezproxy2.library.colostate.edu/10.1111/rec.13469

Larimer County, Larimer County Office of Emergency Management. (2021). *Cameron Peak Fire Risk Assessment.* https://www.larimer.org/sites/default/files/uploads/2021/cpf_risk_assessment_overview_5.24.2021.pdf

Larsen, I.J., MacDonald, L.H., Brown, E., Rough, D., Welsh, M.J., Pietraszek, J.H., Libohova, Z., Benavides-Solorio, J. and Schaffrath, K. (2009). Causes of Post-Fire Runoff and Erosion: Water Repellency, Cover, or Soil Sealing? *Soil Science Society of America Journal, 73*(4), 1393-1407. https://doi-org.ezproxy2.library.colostate.edu/10.2136/sssaj2007.0432

Lintern, A., Webb, J.A., Ryu, D., Liu, S., Bende-Michl, U., Waters, D., Leahy, P., Wilson, P., Western, A. W. (2018). Key factors influencing differences in stream water quality across space. *WIREs Water, 5*(1). https://doi.org/10.1002/wat2.1260

Marmier, V., Dessureault-Rompré, J., Frossard, E., and Caron, J. (2022). Impact of Plant-Based Amendments on Water-Soluble Nitrogen Release Dynamics in Cultivated Peatlands. *Nitrogen, 3*(3), 426-443. https://doi.org/10.3390/nitrogen3030028

Mast, M. A., Murphy, S.F., Clow, D.W., Penn, C.A., and Sexstone, G.A. (2015). Water-quality response to high-elevation wildfire in the Colorado Front Range. *Hydrological Processes, 30*(12), 1811-1823. https://doi-org.ezproxy2.library.colostate.edu/10.1002/hyp.10755

Miller, M.N,. Dandie, C.E., Zebarth, B.J., Burton, D.L., Goyer,C., and Trevors, J.T. (2012). Influence of carbon amendments on soil denitrifier abundance in soil microcosms. *Geoderma, 170*, 48-55. https://doi-org.ezproxy2.library.colostate.edu/10.1016/j.geoderma.2011.11.022

Morris, E.C., and Gibson-Roy, P. (2019). Adding carbon at a standard and a higher rate reduces soil nitrate in a grassy woodland. *Ecological Management & Restoration, 20*(2), 112-118. https://doi-org.ezproxy2.library.colostate.edu/10.1111/emr.12355

Moya, D., González-De Vega, S., Lozano, E., García-Orenes, F., Mataix-Solera, J., Lucas-Borja, M.E., and de las Heras, J. (2019). The burn severity and plant recovery relationship affect the biological and chemical soil properties of *Pinus halepensis* Mill. stands in the short and mid-terms after wildfire. *Journal of Environmental Management, 235,* 250-256. https://doi-org.ezproxy2.library.colostate.edu/10.1016/j.jenvman.2019.01.029

Murphy, J.D., Johnson, D.W., Miller, W.W., Walker, R.F., Carroll, E.F., and Blank, R.R. (2006). Wildfire Effects on Soil Nutrients and Leaching in a Tahoe Basin Watershed. *Landscape and Watershed Process, 35*(2), 479-489. https://doi-org.ezproxy2.library.colostate.edu/10.2134/jeq2005.0144

Murphy, S.F., McCleskey, R.B., Martin, D.A., Writer, J.H., and Ebel, B.A. (2018). Fire, Flood, and Drought: Extreme Climate Events Alter Flow Paths and Stream Chemistry. *Biosciences, 123*(8). https://doi.org/10.1029/2017JG004349

National Weather Service. (2024). NOWData – NOAA Online Weather Data, Monthly Total Precipitation for RUSTIC 9WSW, CO. Retrieved from https://www.weather.gov/wrh/Climate?wfo=bou

NOAA National Weather Service. (n.d.). Precipitation Frequency Data Server. Retrieved [3/8/2024], from https://hdsc.nws.noaa.gov/pfds/pfds_map_cont.html?bkmrk=co

Ortega, R., Miralles, I., Soria, R., Rodriguez-Berbel, N., Villafuerte, A.B., Zema, D.A., and Lucas-Borja, M.E. (2023). Short-term effects of post-fire soil mulching with wheat straw and wood chips on the enzymatic activities in a Mediterranean pine forest. *Science of The Total Environment, 857*(2). https://doi.org/10.1016/j.scitotenv.2022.159489

Paul, M.J., LeDuc, S.D., Lassiter, M.G., Moorhead, L.C., Noyes, P.D., and Leibowitz, S.G. (2022). Wildfire Induces Changes in Receiving Waters: A Review With Considerations for Water Quality Management. *Water Resources Research, 58*(9). https://doi.org/10.1029/2021WR030699

Pierson, D.N., Robichaud, P.R., Rhoades, C.C., and Brown, R.E. (2018). Soil carbon and nitrogen eroded after severe wildfire and erosion mitigation treatments. *International Journal of Wildland Fire, 28*(10), 814-821. https://doi.org/10.1071/WF18193

Pirastru, M., Iovino, M., Marrosu, R., Prima, S.D., Giadrossich, F, and Awada, H. (2022). Large-scale lateral saturated soil hydraulic conductivity as a metric for the connectivity of subsurface flow paths at hillslope scale. *Hydrological Processes, 36*(8). https://doi-org.ezproxy2.library.colostate.edu/10.1002/hyp.14649

Pitman, R.M. and Peace, A. (2021). Mulch *versus* brash: a case study of *in situ* harvesting residue treatment and its effects on C and nutrients in soil and plant uptake during natural rewilding. *Trees, Forests, and People, 6*. https://doi-org.ezproxy2.library.colostate.edu/10.1016/j.tfp.2021.100121

Prats, S. A., Wagenbrenner, J.W., Martins, M.A.S., Malvar, M.C., and Keizer, J.J. (2016). Mid-term and scaling effects of forest residue mulching on post-fire runoff and soil erosion. *Science of The Total Environment, 573*, 1242-1254. https://doi.org/10.1016/j.scitotenv.2016.04.064

Prober, S.M., Thiele, K.R., Lunt, I.A., and Koen, T.B. (2005). Restoring ecological function in temperature grassy woodlands: manipulating soil nutrients, exotic annuals and native perennial grasses through carbon supplements and spring burns. *Journal of Applied Ecology, 42*(6), 1073-1085. https://doi.org/10.1111/j.1365-2664.2005.01095.x

R Core Team (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/

Raoelison, O.D., Valenca, R., Lee, A., Karim, S., Webster, J.P., Poulin, B.A., and Mohanty, S.K. (2023). Wildfire impacts on surface water quality parameters: Cause of data variability and reporting needs. *Environmental Pollution, 317*. https://doi-org.ezproxy2.library.colostate.edu/10.1016/j.envpol.2022.120713

Reever Morghan, K.J. and Seastedt, T.R. (2002). Effects of Soil Nitrogen Reduction on Nonnative Plants in Restored Grasslands. *Restoration Ecology*, *7*(1), 51-55. https://doi-org.ezproxy2.library.colostate.edu/10.1046/j.1526-100X.1999.07106.x

Rhea, A. E., Covino, T. P., & Rhoades, C. C. (2021). Reduced N-Limitation and Increased Instream Productivity of Autotrophic Biofilms 5 and 15 Years After Severe Wildfire. *Journal of Geophysical Research: Biogeosciences, 126(*9), 1–16. https://doi.org/10.1029/2020JG006095

Rhoades, C.C., Entwistle, D., and Butler, D. (2011). The influence of wildfire extent and severity on streamwater chemistry, sediment, and temperature following the Hayman Fire, Colorado. *International Journal of Wildland Fire, 20*, 430-442. https://doi.org/10.1071/WF09086

Rhoades, C.C., Battaglia, M.A., Rocca, M.E., and Ryan, M.G. (2012). Short- and medium-term effects of fuel reduction mulch treatments on soil nitrogen availability in Colorado conifer forests. *Forest Ecology and Management, 276,* 231-238. https://dx.doi.org/10.1016/j.foreco.2012.03.028

Rhoades, C.C., Fornwalt, P.J., Paschke, M.W., Shanklin, A., and Jonas, J.L. (2015). Recovery of small pile burn scars in conifer forests of the Colorado Front Range. *Forest Ecology and Management, 347*, 180-187. http://dx.doi.org/10.1016/j.foreco.2015.03.026

Rhoades, C.C., Hubbard, R.M., and Elder, K. (2017). A Decade of Streamwater Nitrogen and Forest Dynamics after a Mountain Pine Beetle Outbreak at the Fraser Experimental Forest, Colorado. *Ecosystems, 20*, 380-392. https://doi-org.ezproxy2.library.colostate.edu/10.1007/s10021-016-0027-6

Rhoades, C.C., Minatre, K.L., Pierson, D.N., Fegel, T.S., Cotrufo, M.F., and Kelly, E.F. (2017). Examining the Potential of Forest Residue-Based Amendments for Post-Wildfire Rehabilitation in Colorado, USA. *Scientifica, 2017.* https://doi.org/10.1155/2017/4758316

Rhoades, C.C., Chow, A.T., Covino, T.P., Fegel, T.S., Pierson, D.N., and Rhea, A.E. (2019). The Legacy of a Severe Wildfire on Stream Nitrogen and Carbon in Headwater Catchments. *Ecosystems, 22*, 643-657. https://doi.org/10.1007/s10021-018-0293-6

Robichaud, P.R. Ashmun, L.E., Foltz, R.B., Showers, C.G., and Groenier, J.S. (2013). Production and Aerial Application of Wood Shreds as a Post-Fire Hillslope Erosion Mitigation Treatment. Gen. Tech. Rep. RMRS-GTR-307. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 31 p.

Robichaud, P.R., Lewis, S.A., Wagenbrenner, J.W., Ashmun, L.E.., and Brown, R.E. (2013b). Post-fire mulching for runoff and erosion mitigation: Part I: Effectiveness at reducing hillslope erosion rates. *Catena, 105,* 75-92. https://doi.org/10.1016/j.catena.2012.11.015

Rodman, K. C., Davis, K. T., Chambers, M. E., Chapman, T. B., Fornwalt, P. J., Hart, S. J., Marshall, L. A. E., Rhoades, C. C., Schloegel, C. A., Stevens-Rumann, C. S., and Velben, T. T. (2022). *The historic 2020 fire year in northern Colorado and southern Wyoming: A landscape assessment to inform post-fire forest management. Southwest Ecological Restoration Institutes.* https://cfri.colostate.edu/wp-content/uploads/sites/22/2023/01/NFR_2020Fires_Report.pdf

Roebuck Jr., J.A., Bladon, K.D., Donahue, D., Graham, E.B., Grieger, S., Morgenstern, K., Norwood, M.J., Wampler, K.A., Erkert, L., Renteria, L., Danczak, R., Fricke, S., and Meyers-Pigg, A.N. (2022). Spatiotemporal Controls on the Delivery of Dissolved Organic Matter to Streams Following a Wildfire. *Geophysical Research Letters, 49*(16). https://doi.org/10.1029/2022GL099535

Rust, A.J., Hogue, T.S., Saxe, S., and McCray, J. (2018). Post-fire water-quality response in the western United States. *International Journal of Wildland Fire, 27*(3), 203-216. https://doi.org/10.1071/WF17115

Rust, A.J., Saxe, S., McCray, J., Rhoades, C.C., and Hogue, T.S. (2019). Evaluating the factors responsible for post-fire water quality response in forests of the western USA. *International Journal of Wildland Fire, 28*, 769-784. https://doi.org/10.1071/WF18191

Santos, R., Wymore, A.S., Jackson, B.K., Mažeika, S., Sullivan, P., McDowell, W.H., and Berhe, A.A. (2019). Fire severity, time since fire, and site-level characteristics influence streamwater chemistry at baseflow conditions in catchments of the Sierra Nevada, California, USA. *Fire Ecology, 15*(3). https://doi.org/10.1186/s42408-018-0022-8

Schueler, T.R., Fraley-McNeal, L., and Cappiella, K. (2009). Is Impervious Cover Still Important? Review of Recent Research. *Journal of Hydrologic Engineering,* 309-315. http://dx.doi.org/10.1061/(ASCE)1084-0699(2009)14:4(309)

Serpa, D., Ferreira, R.V., Machado, A.I., Cerqueira, M.A., Keizer, J.J. (2020). Mid-term post-fire losses of nitrogen and phosphorus by overland flow in two contrasting eucalypt stands in north-central Portugal. *Science of The Total Environment, 705.* https://doi.org/10.1016/j.scitotenv.2019.135843

Skiba, U. (2008). Denitrification. In Jorgenson, Sven Eric, Fath, and Brian, D (Eds.), *Encyclopedia of Ecology* (pp. 866-870). https://nora.nerc.ac.uk/id/eprint/13470

Shaver, K.C., Neese, W.D., and Braddock, W.A. (1988). Geological map of the Rustic quadrangle, Larimer County, Colorado, U.S. Geological Survey, Geologic Quadrangle Map GQ-1619, scale 1:24,000. https://doi.org/10.3133/gq1619

Smith, H.G., Sheridan, G.J., Lane, P.N.J., Nyman, P., and Haydon, S. (2011). Wildfire effects on water quality in forest catchments: A review with implications for water supply. *Journal of Hydrology, 396*(1-2), 170-192. https://doi.org/10.1016/j.jhydrol.2010.10.043

Stieglitz, M., Shaman, M., McNamara, J., Engel, V., Shanley, J., and Kling, G.W. (2003). An approach to understanding hydrologic connectivity on the hillslope and the implications for nutrient response. *Global Biogeochemical Cycles, 17*(4). https://doi.org/10.1029/2003GB002041

Stottlemyer, R., and Troendle, C.A. (1999). Effect of subalpine canopy removal on snowpack, soil solution, and nutrient export, Fraser Experimental Forest, CO. *Hydrological Processes, 13*, 2287-2299. https://doi-org.ezproxy2.library.colostate.edu/10.1002/(SICI)1099-1085(199910)13:14/15%3C2287::AID-HYP883%3E3.0.CO;2-F

Torok, K., Szili-Kovacs, T., Halassy, M., Toth, T., Hayek, Zs., Paschke, M.W., and Wardell, LJ. (2000) Immobilization of soil nitrogen as possible method for the restoration of sandy grassland. *Applied Vegetation Science, 3*(1), 7-14. https://doi-org.ezproxy2.library.colostate.edu/10.2307/1478913

Uddin, M.N., Robinson, R.W., and Asaeda, T. (2020). Nitrogen immobilization may reduce invasibility of nutrient enriched plant community invaded by *Phragmites australis*. *Scientific Reports, 10*(1601). https://doi.org/10.1038/s41598-020-58523-4

U.S. Geological Survey. (2023). 3D Elevation Program Point Cloud [Elevation Source Data (3DEP)]. https://apps.nationalmap.gov/downloader/#/

Uwituze, Y., Nyiranzea, J., Jiang, Y., Dessureault-Rompré, J., and Fraser, T.D. (2023). Soil C, N, and P bioavailability and cycling following amendment with shrub willow chips. *Canadian Journal of Soil Science, 103*(3), 1-18. http://dx.doi.org/10.1139/CJSS-2022-0126

Vourlitis, G., Steinecke, D., Martinez, T., Konda, K., Rendon, R., Hall, V., Khor, S., and Sethuramann, A. (2022). Fire and post-fire management alters soil microbial abundance and activity: A case study in semi-arid shrubland soils. *Applied Soil Ecology, 171*. https://doi-org.ezproxy2.library.colostate.edu/10.1016/j.apsoil.2021.104319

Wagenbrennar, J.W., MacDonald, L.H., and Rough, D. (2006). Effectiveness of three post-fire rehabilitation treatments in the Colorado Front Range. *Hydrological Processes, 20*(14), 2989-3006. https://doi.org/10.1002/hyp.6146

Wan, S., Hui D., and Luo Y. (2001). Fire effects on nitrogen pools and dynamics in terrestrial ecosystems: a meta-analysis. *Ecological Applications, 11*(5), 1359-1365. https://doi.org/10.1890/1051-0761(2001)011[1349:FEONPA]2.0.CO;2

Wang, J., Chen, Z., Xu, C., Elrys, A.S., Shen, F., Cheng, Y., and Chang, S.X. (2021). Organic amendment enhanced microbial nitrate immobilization with negligible denitrification nitrogen loss in an upland soil. *Environmental Pollution, 288.* https://doi-org.ezproxy2.library.colostate.edu/10.1016/j.envpol.2021.117721

Web Soil Survey. (2023). *Arapaho-Roosevelt National Forest Area, Colorado, Parts of Boulder, Clear Creek, Gilpin, Grand, Park and Larimer Counties.* U.S. Department of Agriculture, Natural Resources Conservation Service. Retrieved from https://websoilsurvey.nrcs.usda.gov/app/

Weber, K.T., and Yadav, R. (2020). Spatiotemporal Trends in Wildfires across the Western United States (1950-2019). *Remote Sensing and Pyrogeography, 12*(18), 2959. https://doi.org/10.3390/rs12182959

Westerling, A.L.R. (2016). Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences, 371*(1696). https://doi.org/10.1098/rstb.2015.0178

WRCC. (2016). Period of Record Monthly Climate Summary Rustic 9 WSW, Colorado (Station 057296). Retrieved from https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?co7296

Yano, Y., Qubain, C., Holyman, Z., Jencso, K., and Hu, J. (2019). Snowpack influences spatial and temporal soil nitrogen dynamics in a western U.S. montane forested watershed. *Ecosphere, 10*(7). https://doi.org/10.1002/ecs2.2794