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The Legacy of a Severe Wildfire on Stream Nitrogen and Carbon in Headwater Catchments

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ABSTRACT

Large, high-severity wildfires alter the physical and biological conditions that determine how catchments retain and release nutrients and regulate streamwater quality. The short-term water quality impacts of severe wildfire are often dramatic, but the longer-term responses may better reflect terrestrial and aquatic ecosystem recovery. We followed streamwater chemistry for 14 years after the largest fire in recorded Colorado history, the 2002 Hayman Fire, to characterize patterns in nitrogen (N) and carbon (C) export. Throughout the postfire period, stream nitrate and total dissolved N (TDN) remained elevated in 10 burned catchments relative to pre-burn periods and 4 unburned control catchments. Both the extent of fire in a catchment and wildfire severity influenced stream N concentrations. Nitrate was more than an order of magnitude higher in streams draining catchments that burned to a high extent (> 60% of their areas) compared to unburned catchments. Unburned catchments retained more than 95% of atmospheric N inputs, but N retention in burned catchments was less than half of N inputs. Unlike N, stream C was elevated in catchments that burned to a lesser extent (30–60% of their areas burned), compared to either unburned or extensively burned catchments. Remotely sensed estimates of upland and riparian vegetation cover suggest that burned forests could require several more decades before forest cover and nutrient demand return to pre-fire levels. The persistent stream N increases we report are below drinking water thresholds, but exceed ecoregional reference concentrations for healthy stream ecosystems and indicate that extensively burned headwater catchments no longer function as strong sinks for atmospheric N. Combined with increasing trends in wildfire severity and elevated N deposition, our findings demonstrate the potential for substantial post-wildfire changes in ecosystem N retention and have implications for nutrient export to downstream waters.

Key words: watershed biogeochemistry; forest disturbance; nitrogen cycling; streamwater nutrients; dissolved organic carbon; Colorado; nutrient retention; wildfire severity; Ponderosa pine forest.

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INTRODUCTION

Wildfires shape the composition, structure, and function of most western North American forest ecosystems (Agee 1998; Turner 2010). Fire frequency, size, and severity have all increased in recent decades (Westerling and others 2006), raising concerns about the ability of forests to recover and maintain their capacities to provide clean water and other ecosystem services under changing wildfire conditions (Millar and Stephenson 2015). Combustion of forest biomass and organic soil layers drastically increase short-term nutrient and C losses (Bormann and others 2008; Homann and others 2011) and expose catchments to post-fire erosion (Benavides-Solorio and MacDonald 2005; Larsen and others 2009). Wildfires influence streamwater quality and nutrient export by reducing plant demand, increasing soil nutrient availability in upland and riparian environments, and increasing erosional inputs of fine and coarse mineral materials (Wan and others 2001; Certini 2005; Turner and others 2007). Hydrologic connectivity and transport from uplands to stream channels change with post-fire reconfiguration of land cover and enhanced hillslope loading to the channel network (Wagner and others 2014; Hallema and others 2017). The legacies of fires may also alter the in-stream physical and biological processes that regulate nutrient uptake and retention (Triska and others 1989a, 1989b; Covino and others 2010).

The impacts of wildfires increase with their relative extent and severity (Minshall and others 1989; Riggan and others 1994). High-severity wildfires burn nearly all vegetation and consume most surface organic layers (soil O horizons). Exposed mineral soils are highly susceptible to losses of sediment, nutrients, and carbon. Losses are typically less for lower severity fires since the O horizon remains intact (Benavides-Solorio and MacDonald 2005; Keeley 2009). Streamwater nitrate and sediment export, for example, were higher and more variable in catchments affected by extensive, high-severity burning during Colorado's 2002 Hayman Fire relative to less extensively burned landscapes (Rhoades and others 2011).

The short-term effects of wildfire on water quality have been characterized following many individual fires (Ranalli 2004; Smith and others 2011; Costa and others 2014). For example, based on research of dry conifer forests, post-fire expectations include dramatic, initial sediment losses followed by return to pre-fire conditions within several years, as plant cover increases and overland flow declines (Pann-

kuk and Robichaud 2003; Larsen and others 2009). The longer-term consequences of wildfire have been followed in fewer cases (Dunnette and others 2014), though a recent review found increased N and phosphorus (P) export as the most common water quality response the first 5 years after western North American wildfires (Rust and others 2018). The outcome of wildfire disturbances is determined by unique combinations of site conditions, wildfire characteristics, and post-fire ecological interactions (Turner 2010), yet the factors that control long-term recovery trajectories remain almost unexamined for many ecosystem types (Romme and others 2011; Silins and others 2014). Any lasting post-fire changes in source water quality have implications for water treatment utilities (Emelko and others 2011; Bladon and others 2014; Martin 2016) and their ability to deliver clean water to populations that rely on forested catchments for drinking water (Hutson and others 2004). Over longer time periods (> 5 years), elevated N exports may have consequences for chronic eutrophication of downstream waters (Gooday and others 2009). Additionally, evaluating long-term recovery from disturbance can provide fundamental insight into ecosystem function.

After initial erosion events pass, the concerns of citizens and land management agencies about burned catchments typically recede. However, the biogeochemical processes that influence ecosystem productivity, nutrient retention and losses, and streamwater quality continue to respond for years after a fire. Changing climate and increased human-caused ignitions will increase wildfire frequency (Dennison and others 2014; Harvey 2016; Balch and others 2017; Schoennagel and others 2017). A greater understanding of post-fire changes that control stream nutrient and C retention and loss will benefit land managers concerned with sustaining ecosystem productivity and clean water supply. During 2015 and 2016, we revisited streams that were sampled the first 5 years after the 2002 Hayman Fire (Rhoades and others 2011) to gain insight on long-term, post-fire dynamics. In total, we sampled ten burned and four unburned headwater catchments to assess the effect of wildfire extent, burn severity, and status of upland and riparian vegetation on water quality 13 and 14 years after the fire.

METHODS

Study Site

The 2002 Hayman Fire burned more than 550 km^2 within tributaries of the Upper South Platte River

drainage, located 50 km southwest of Denver, Colorado (Graham 2003). This water source supplies most of the drinking water to the Denver metropolitan area as well as to agricultural and industrial users. The fire burned in the lower montane zone (1980–2750 m) of Colorado's Front Range, in forests dominated by ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Annual precipitation averages 41 cm (WRDC 2017) with equal contribution of summer rain and winter snow fall. The majority of the burned area is underlain by the Pikes Peak batholith, a coarse-grained biotite and hornblende–biotite granite (Bryant and others 1981). Soils are weakly developed (Typic Ustorthents), excessively drained, coarse sandy loams (Cipra and others 2003). Depth to bedrock ranges from 25 to 50 cm, and coarse fragments represent 25–50% of the soil volume.

This study included fourteen first- and second-order tributaries that span from 4 to 40 km^2 in catchment area (Table 1). Each stream drains an independent catchment. We sampled streamwater quality in four unburned catchments and ten burned catchments that had wildfire extent ranging from 33 to 100%. Crown and ground cover consumption estimates derived from satellite imagery and ground-based observations were used to estimate that 35 and 16% of the Hayman Fire burned at high and moderate severity, respectively

(Robichaud and others 2003). A recent survey revised the coverage of high- and moderate-severity burning to 52 and 18% (Wang and Zhang 2017), but we retained initial post-fire estimates to permit comparison with earlier work (Rhoades and others 2011).

Sampling and Analysis

Streamwater Characterization

Streamwater samples were collected and analyzed for dissolved nitrogen, dissolved organic carbon, turbidity, and suspended sediment. Water samples were collected in opaque HDPE plastic bottles. Plastic bottles were washed with deionized water (electrical conductivity < 1.0 µS cm^{-1}) prior to use and then triple-rinsed with streamwater at the time of sampling. Samples were refrigerated after collection and then filtered through 0.45-µm pore-size membrane filters (Millipore Durapore PVDF, Billerica, MA). Total dissolved nitrogen (TDN) and dissolved organic carbon (DOC) samples were collected in pre-combusted (heated for 3 h at 500°C) amber and glass bottles and then filtered through 0.7-µm pore-size glass fiber filters (Millipore Corp, Burlington, MA).

Streamwater nitrate (NO$_3$–N) and ammonium (NH$_4$–N) concentrations were determined by ion chromatography with electrical conductivity detection, using an AS12A Anion-Exchange col-

Table 1. Tributaries of the South Platte River, Colorado, Affected by or Adjacent to the 2002 Hayman Fire

Burn extent	Catchment area			Burn extent by wildfire severity		
Catchment	Total (km^2)	Burned (km^2)	Burned (%)	Low (%)	Moderate (%)	High (%)
High extent burned						
East Turkey	4.2	4.2	100.0	5.6	13.9	80.5
Wildcat	5.1	5.1	99.8	18.1	8.7	73.0
Brush*	5.9	5.4	91.4	29.1	3.3	59.0
Corral	10.3	8.6	84.1	10.7	3.7	69.8
Turkey	57.8	45.4	78.7	39.9	18.3	20.4
Fourmile*	20.6	15.4	74.4	12.3	10.5	51.6
Low extent burned						
Burnt Pine	9.3	5.3	57.7	10.1	2.2	45.4
Cabin*	19.8	7.2	36.5	12.7	0.8	23.0
Wigwam*	43.3	15.3	35.3	10.6	1.3	23.5
Hackett	4.3	1.4	33.0	24.7	8.1	0.3
Unburned						
Fern*	18.6	0.0	0.0	0.3	0.0	0.0
Sugar*	34.3	0.0	0.0	0.0	0.0	0.0
Russel	6.4	0.0	0.0	0.0	0.0	0.0
Jenny	4.6	0.0	0.0	0.0	0.0	0.0

All streams are first- and second-order tributaries. Six catchments (*) were sampled monthly throughout the 2015 and 2016 water years. All 14 streams were sampled twice each summer (June and August) in 2015 and 2016.

umn with a AG12A guard column for NO_3-N (Dionex Corp., Sunnyvale, CA) and a IC-Pak Cation M/D column for NH_4-N (Waters Corp., Millford, MA) (APHA 1998a). Detection limits were 2 and 8 μg N l^{-1} for nitrate–N and ammonium–N. Total dissolved N (TDN) and dissolved organic C (DOC) were determined by high-temperature combustion catalytic oxidation using a Shimadzu TOC-V$_{CPN}$ total organic carbon analyzer (Shimadzu Corp., Columbia, MD). Detection limits for TDN and DOC were 0.02 and 0.2 mg l^{-1}. Concentrations rarely fell below detection limits ($<$ 1% of samples for any analyte); those that did were replaced by one half the detection limit concentration (Helsel and Hirsch 1992). Dissolved organic N (DON) was calculated as the difference of TDN and dissolved inorganic N (DIN = nitrate–N plus ammonium–N). Suspended sediment was collected in 1-l bottles, filtered onto 0.45-μm filters, and dried at 105°C (APHA 1998b). Turbidity was measured in the 1-l samples using the nephelometric method (APHA 1998c) (Hach Scientific, Loveland, CO).

Monthly throughout the 2015 and 2016 water years (October–September), we sampled two streams in unburned catchments, two in catchments with low extent burned, and two in catchments with high extent burned (Table 1). Discharge was measured concurrently with streamwater sampling to flow-weight N and C concentrations and calculated catchment export using the velocity-area method with an OTT Hydromet MF Pro flowmeter (Hach Company, Loveland, CO). Monthly discharge was the sum of measurements recorded at 0.6 the stream depth in 10–30-cm-wide intervals across each stream cross section (n = 10–15 measurements per stream cross section).

We evaluated stream N and C data in monthly, seasonal, and annual time steps; seasonal divisions correspond to the rising limb (February–May), falling limb (June–September), and base flow (October–January) of the streamflow hydrograph. In addition to monthly sampling in 6 streams, we synoptically sampled all 14 catchments (Table 1) twice each summer (June and August) during 2015 and 2016. Water temperature was measured at 20-min intervals in the six monthly sampling streams using Hobo Water Temp Pro v2 data loggers installed on the stream bottom (U22-001; OnSet Corp, Bourne, MA).

Vegetation Structure

We classified the riparian condition of the ten burned catchments included in this study as follows. We partitioned woody plant cover into three cover classes (exposed: $<$ 30%; moderate: 30–80%; dense: $>$ 80%) using publicly available aerial imagery (FSA 2015) within 10-m longitudinal increments extending 20 m on each side of the stream. We also conducted field surveys of each study stream to confirm the general composition and canopy condition of riparian trees and shrubs within the three cover classes. Unburned catchments were excluded from this analysis, because it was not possible to evaluate riparian condition remotely.

We analyzed annual changes in vegetation starting prior to the fire and extending until the current resampling (2000–2016) using normalized difference vegetation index (NDVI). Growing season (May–July) NDVI data (Google Earth Climate Engine, Landsat 7/8, 30-m resolution) was partitioned into upland landscapes and 30-m-wide riparian zones in the four burned and two unburned catchments used for monthly stream sampling. Lower NDVI values correspond to poorly vegetated areas, and higher values are associated with denser vegetation cover. Within burned catchments, differenced normalized burn ratio (dNBR) maps were used to constrain NDVI changes to areas burned at high and moderate severity. Stratification of landscape locations and burn severity patches and calculation of annual NDVI were conducted using geospatial software (ArcGIS Desktop, V. 10.3.1, Environmental Systems Research Institute, Redlands, CA).

We evaluated the relation between stream N concentration and burn extent or proportional area burned at high severity for all fourteen synoptically sampled catchments using least-squares linear regression (SPSS V. 22, IBM CO, Chicago, IL). Comparison of stream concentrations and export in unburned and burned catchments sampled at monthly time steps were partitioned into rising limb, falling limb, and base flow periods based on regional streamflow patterns (Rhoades and others 2011). We tested the effect of wildfire extent within seasons using a mixed-model analysis of variance (SPSS V. 22, IBM CO, Chicago, IL) with burn extent class (unburned, low extent burned, high extent burned) and season as fixed effects and catchment as a random effect. Levene's statistic was used to test homogeneity of variance, and data were log-transformed prior to conducting analysis of variance when needed. Statistical significance is reported at $\alpha \leq 0.05$.

RESULTS

Stream Nitrogen and Carbon

The effects of the Hayman Fire on stream N have persisted for more than a decade. Across fourteen

headwater catchments, wildfire extent and severity remain good predictors of summer stream nitrate and TDN concentrations (Figure 1). The total burn extent within a catchment explained 76% of the variation in nitrate concentrations and 56% of variation in total dissolved N concentrations, while the extent burned at high severity explained only slightly less variation (Figure 1). Relative to unburned catchments, stream nitrate was roughly 10 times higher in catchments with greater than 60% total burn extent or greater than 40% high-severity burn extent (Figure 1). Stream ammonium concentrations did not differ between burned and unburned catchments.

In the six catchments sampled monthly, mean nitrogen concentrations were higher in burned compared to unburned catchments, regardless of season (Figure 2). Catchments that burned to a high extent had 16 times higher concentrations of nitrate and 5 times more TDN than unburned catchments. Also, N concentrations were significantly higher in catchments burned to a high extent relative to those burned to a low extent (Figure 2). Ammonium concentrations were unaffected by burning and averaged 0.04 mg N l^{-1} overall. Nitrate comprised 33% of TDN averaged across seasons in unburned watersheds, but 61% in catchments with low burn extent and 89% in catchments with high burn extent. In unburned catchments, DIN was split evenly between nitrate and ammonium. In contrast, in catchments with low and high burn extents, nitrate comprised 84 and 94% of DIN.

Dissolved organic C (Figure 2) and N (DON; not shown) concentrations were both highest in catchments with low burn extent and, on average, were 1.5–2 times higher than unburned or high-burn-extent catchments. Stream DOC varied with
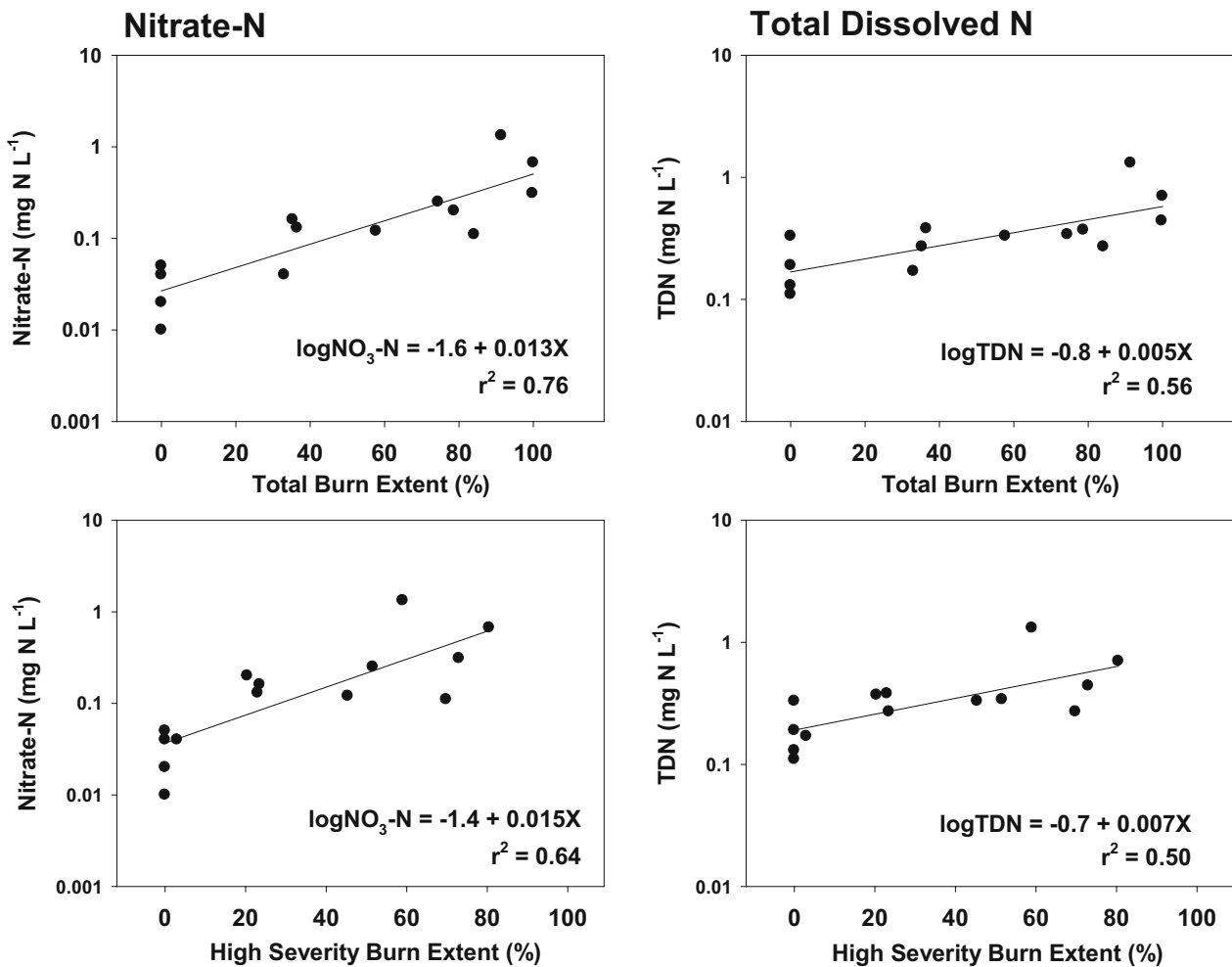

Figure 1. Relations between total burn extent within a catchment and the extent burned by high-severity wildfire and stream nitrate–N (left) and total dissolved N (right). Values are June and August 2015 and 2016 mean concentrations for four unburned and ten catchments burned by the 2002 Hayman Fire (Table 1).
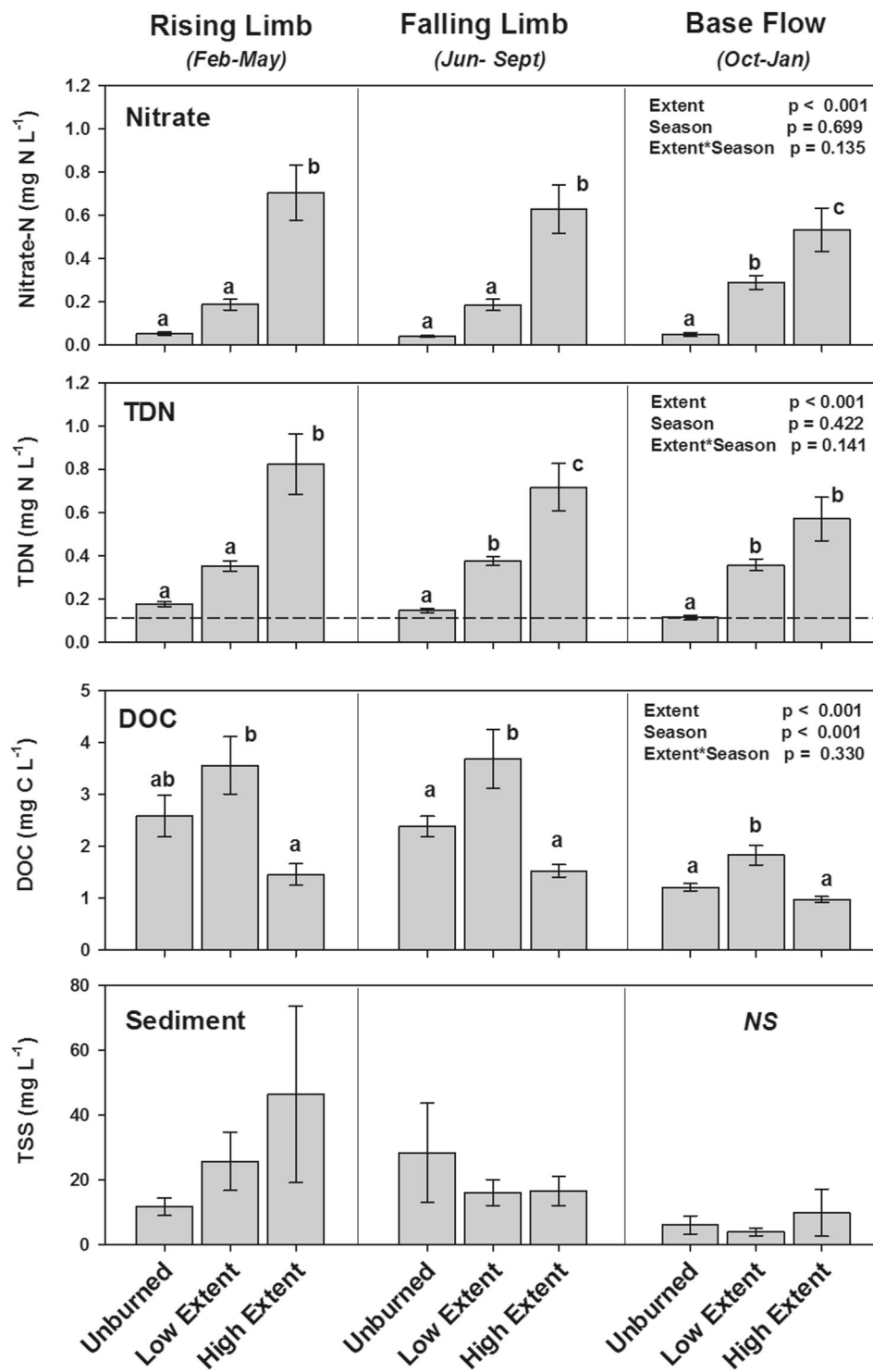
Figure 2. Seasonal mean nitrogen, carbon and total suspended sediment (TSS) concentrations from four catchments burned by the 2002 Hayman Fire and two nearby unburned catchments (Table 1). Burn extent classes as follows: high extent: > 60% burned, low extent: 30–60% burned and unburned. Means were derived from 2015 and 2016 monthly samples for two catchments per burn extent class (n = 12 for each season). The *dashed line* on the TDN panel denotes the proposed TN threshold concentrations for least-impaired reference streams in the Western Forest Region (US EPA 2000).

the seasonal stream hydrograph (Figure 3), with lowest average concentrations during fall–winter base flow conditions (October–January) as opposed to the rising and falling limbs in February–May and June–September, respectively (Figure 2). Averaged across seasons, DON comprised 35% of TDN in unburned catchments compared to 6% in high-burn-extent catchments. The ratio of streamwater C:N, measured as DOC to TDN, differed among unburned and extensively burned catchments, as did the relation between C:N and nitrate–N. Average C:N was 18 in unburned catchments (range 13–27) and 8 in catchments with high burn extent (range 1–16). Suspended sediment did not vary with extent burned or among burned and unburned catchments.

N and C Export

During our 2015 and 2016 sampling, annual TDN export from unburned catchments averaged

Figure 3. Nitrogen, carbon, and TSS export from catchments burned by the 2002 Hayman Fire and for nearby unburned catchments. Means were derived from 2015 and 2016 monthly samples for two catchments per burn severity class (Table 1).

0.12 kg N ha^{-1} compared to 0.44 and 0.65 kg N ha^{-1} from catchments with low and high extent burned (Figure 3). Nitrate–N export averaged 0.03 (unburned), 0.18 (low burn extent), and 0.56 (high burn extent) kg N ha^{-1} y^{-1}, and annual export from catchments with high burn extent was 19 times higher than from unburned catchments and 3 times higher than from catchments with low burn extent. Nitrate represented an increasing proportion of TDN across the burn extent gradient, averaging 21% in unburned catchments, 44% in catchments with low burn extent, and 85% of TDN catchments with high burn extent. Monthly N export peaked in May along with streamflow, and May export comprised 30–35% of annual fluvial N flux.

Both DOC (Figure 3) and DON export (not shown) were about 3 times higher in catchments with low burn extent, compared to unburned catchments and those with high burn extent. Although DON comprised about half of the TDN exported from unburned and low-burn-extent catchments, it accounted for only 11% of TDN export from high-burn-extent catchments. Sediment losses were 4 and 5 times higher in low- and high-burn-extent catchments compared to unburned catchments, with 71 and 84% of those losses occurring during peak streamflow in May (Figure 3).

Post-fire Recovery

Average nitrate concentrations remained elevated for the entire sampling period relative to pre-fire concentrations in catchments with both low and high burn extent (Table 2). For catchments with low wildfire extent, maximum concentrations of nitrate have declined by 76% since the first post-fire evaluation period. However, maximum nitrate concentrations in catchments with high burn extent declined by only 30%. Mean nitrate concentrations have not declined as much as maximum concentrations, with only a 12% decline in low extent and a 10% decline in high-extent-burn catchments 13–14 years post-fire (Table 2). In contrast to stream nitrate, turbidity decreased much more, with 95 and 98% decreases in low- and high-burn-extent catchments (Table 2). Accordingly, turbidity levels are currently similar among burned and unburned catchments.

Streamwater chemistry varied with current catchment vegetation. Stream nitrate–N increased exponentially with the extent of riparian exposure, as defined by the extent of woody cover in the streamside zones of burned catchments (Figure 4).
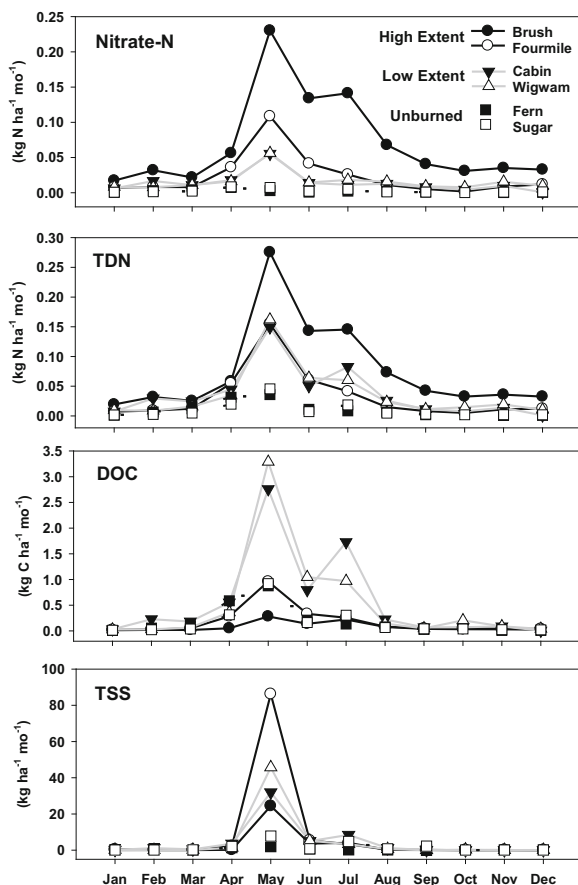
Table 2. Stream Nitrate and Turbidity 1 year Prior to the 2002 Hayman Fire, During 5 Post-fire Years, and the 13–14-Year Post-fire Resampling

Period	Burn extent	Nitrate–N (mg l^{-1})			Turbidity (NTUs)			Catchments
		Mean	SD	Max	Mean	SD	Max	
Pre-fire (2001)	Unburned	0.04	0.0	0.1	3.4	2.7	11.3	Brush, Sugar, No-Name
Post-fire period 1 (1–5 years)	Unburned	0.04	0.0	0.2	7.8	9.4	43.0	Sugar, No-Name
	Low burn extent	0.25	0.3	2.1	30.2	55.4	220.3	Wigwam, West
	High burn extent	0.69	0.6	2.3	81.1	120.1	481.0	Brush, Fourmile
Post-fire period 2 (13 and 14 years)	Unburned	0.05	0.0	0.1	2.1	3.2	17.0	Sugar, Fern
	Low burn extent	0.22	0.1	0.5	1.7	1.8	7.5	Wigwam, Cabin
	High burn extent	0.62	0.5	1.6	2.0	3.3	19.0	Brush, Fourmile

Pre-fire period sampling included streams that were both burned (Brush) and unburned (Sugar, No-Name) by the Hayman Fire. West and No-Name were excluded from post-fire period 2 analysis due to their large or small catchment size relative to the other monthly sample catchments.
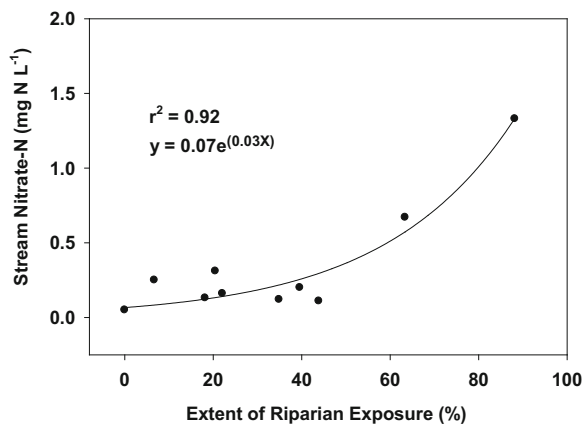

Figure 4. Relation between stream nitrate and the extent of exposed riparian corridors, defined as < 30% woody cover within 20 m of either side of stream. Values are 2015 and 2016 summer mean concentrations for ten catchments burned by the 2002 Hayman Fire (Table 1). Unburned catchments were excluded, as it was not possible to remotely examine riparian condition.

The catchment with the highest nitrate–N concentration had sparse (< 30%) riparian cover along 88% of its stream length. Upland and riparian vegetation cover estimated by NDVI declined by 63% in 2003, the year after the Hayman Fire (Figure 5). From 2003 to 2016, burned areas recovered to within 25% of the pre-fire NDVI on average, with little difference between the riparian and upland zones. Based on this estimate of annual increase, recovery to pre-fire NDVI will require about three and a half decades after the fire (two decades beyond our current sampling period).

During 2016, streamwater temperature was significantly higher in burned catchments compared to unburned streams (Figure 6). Averaged annu-ally, streams with high burn extent were 1.6°C warmer than unburned catchments, and those with low burn extent were 0.8°C warmer. The largest differences were in the spring and fall when temperatures were 2–3°C warmer in extensively burned relative to unburned catchments.

DISCUSSION

Post-fire Water Quality

Our findings characterize the lasting effect of the Hayman Fire on the biogeochemical processes that retain and release N and C in headwater catchments and demonstrate that the magnitude and duration of the changes are proportional to fire severity and extent. Prior to the Hayman Fire, average annual nitrate export from headwater tributaries of the Upper South Platte River was 0.03 kg N ha^{-1} (Rhoades and others 2011). This low level of N release is the net result of 97% retention of nitrate–N inputs in wet deposition (1.1 kg N ha^{-1} y^{-1}; NADP 2017). During the current study, nitrate export averaged 0.56 kg N ha^{-1} annually from catchments with high burn extent (Figure 2). This represents only 48% retention of the atmospheric nitrate input to these catchments. In the 14 years since the fire, we estimate that export of nitrate (7.8 kg N ha^{-1}) and TDN (9.1 kg N ha^{-1}) was close to an order of magnitude greater than export from unburned catchments (0.4 and 1.4 kg N ha^{-1}). We did not sample large nutrient export events associated with storm events, due to logistical, site-access limitations, so our estimates likely represent a lower bound on N export. Overall, our study shows that headwater catchments that burned to a high extent no longer function as strong sinks for atmospheric N. This
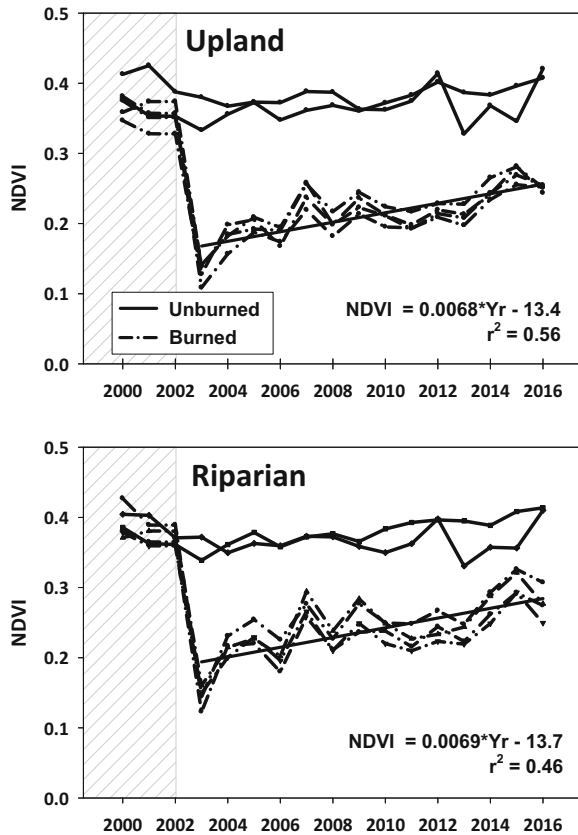
Figure 5. Average growing season (May–July) normalized difference vegetation index (NDVI) for riparian and upland landscapes in four catchments burned by the 2002 Hayman Fire and two unburned catchments that were sampled monthly during this study (Table 1). Post-fire NDVI changes were restricted to areas altered by high-severity crown fire. Hatched areas denote pre-fire data. The linear trend of NDVI recovery extends from 2003, the first growing season after the fire.

Figure 6. Monthly average stream temperatures in tributaries affected by the 2002 Hayman Fire and nearby unburned streams. Data were collected at 20-min intervals in two streams per class during 2016 (Table 1). *Double asterisks* (**) denote significant differences between monthly mean temperature among each of the three burn extent classes ($\alpha = 0.05$). *One asterisk* (*) above the monthly mean data indicates that high-extent catchments differ from the other 2 classes. Conversely, one asterisk below the monthly mean data indicates that unburned catchments differ from the two burned catchment classes.

lack of N retention has importance to downstream ecosystems, particularly when evaluated in association with shifts in C exports, as coupled C and N cycling control aquatic ecosystem denitrification (Zarnetske and others 2011; Fork and Heffernan 2014). Additionally, given increased atmospheric N deposition in the Colorado Front Range (Baron and others 2000; Bowman and others 2012), the persistent decrease in post-fire N retention has amplified consequences.

Though post-fire stream nitrate and DOC concentrations do not pose a direct threat to human health, these changes have implications for both water treatment and aquatic ecosystem function in the Upper South Platte. Average stream nitrate–N concentrations in catchments with low and high burn extent were 6 and 16 times above pre-fire levels (Table 2) though mean and maximum ni-
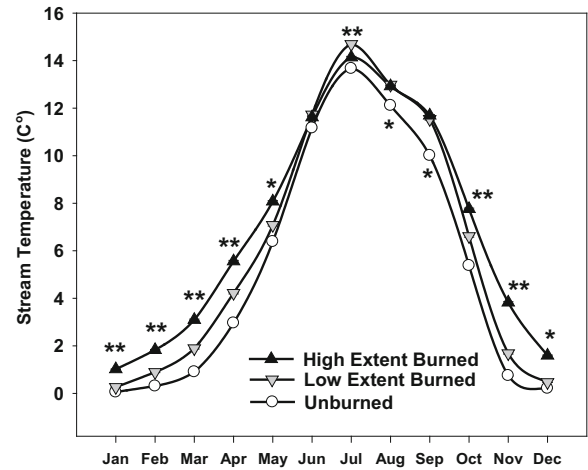
trate concentrations in burned catchments fell well below the national drinking water standard for nitrate–N (10 mg N l^{-1}; USEPA 2003). In addition to changes in stream N concentrations and export, DOC dynamics also shifted as a function of wildfire. For example, DOC concentrations and export remain elevated in catchments burned to a low extent and diminished in those burned to a high extent 14 years post-fire. Because the majority of organic C enters the stream network in headwater locations, higher-order systems downstream tend to rely on organic matter supplied from upstream (Raymond and others 2016). Consequently, shifts in DOC export in low and high extent burns may alter downstream aquatic ecology in contrasting ways. Further, not only are DOC exports decreased in high-extent-burn catchments, but the character and reactivity of the exported DOC may be altered as well, further exacerbating impacts on downstream ecosystems. Conversely, the persistent increase in DOC exported from catchments with a low extent of wildfire may affect municipal water treatment and could promote enhanced aquatic ecosystem heterotrophic respiration downstream due to increased DOC delivery. These changes in DOC and N delivery are concerning because alteration of basal resource supply (DOC, N, and P) can

induce shifts in aquatic ecosystem community composition and associated function (Slavik and others 2004). From a societal and management perspective, our ongoing analysis of streamwater C composition and the hazardous compounds created by drinking water chlorination (disinfection by products, DPBs) indicates significantly higher formation potential for trihalomethanes and other DBPs in study catchments that had a low extent of wildfire, compared to unburned catchments or those burned to a high extent (A. Chow, unpublished). Consequently, the long-lasting changes in post-fire C and N export may have substantial consequences to coupled C and N cycling and ecosystem function in downstream waters and create hazardous water supply issues.

Water quality has become a larger issue for stream biota since the Hayman Fire. Prior to the fire, stream temperature and sediment were identified as water quality concerns in Upper South Platte tributaries (Colorado 2002) with specific relevance to sport fisheries and other aquatic resources. Rainbow (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) density and biomass as well as the abundance of large individuals have declined by 40–50% in the Upper South Platte River since 2002 compared to 7 years prior to the fire (Colorado Parks and Wildlife 2017). A number of burned catchments have been added to Colorado's 303d list of impaired waters (Colorado 2016a) for dissolved oxygen (DO), temperature, reactive iron, and threats to aquatic life since the fire. We found stream temperature, which affects DO concentration, remained elevated 14 years after the fire (Figure 6). In burned catchments, we also found that stream nitrate and TDN frequently exceeded concentration thresholds established to signal concerns regarding public water supply, aquatic life, and other beneficial uses in Colorado's cold rivers and streams (1.25 mg TN l^{-1}; Colorado 2016b). Further, in catchments with both low and high wildfire extent, nitrate and TDN concentrations greatly exceeded N concentrations representative of 'least-disturbed' reference streams of the Western Forest Region (0.12 mg TN l^{-1} and 0.014 mg nitrate–N l^{-1}; USEPA 2000). In contrast to sustained stream nutrient and C responses, post-fire sediment concerns have abated for a number of Upper South Platte tributaries, and they have been delisted since the fire (Colorado 2016b).

Persistent Biogeochemical Effects

Almost 15 years after the Hayman Fire, we found little indication that elevated nitrate concentrations and export from catchments with extensive wildfire were returning to pre-fire levels (Table 2). We also found elevated DOC in streams draining catchments that burned to a low extent (Figures 2 and 3). Post-fire increases in soil N availability, a likely source of the elevated stream N, are the net result of decreased nutrient demand following the loss of forest vegetation and increased supply of inorganic N forms via mineralization and nitrification (Wan and others 2001; Turner and others 2007; Rhoades and others 2015). Changes in stream DOC are the consequence of organic matter losses during wildfire combustion (Harden and others 2000; Writer and others 2014) and erosion (Homann and others 2011) compounded by reduced post-fire allochthonous C inputs from upland and riparian vegetation (Minshall and others 1989).

Little is known about long-term patterns of post-fire N and C release from soils and stream N export (DeLuca and others 2002; Jiménez-Esquilín and others 2008; Hanan and others 2016), though current understanding of soil N processes is consistent with our catchment-scale observations. Mineral and organic soil layers are the largest reservoirs of nitrogen (N) in most forest ecosystems (Schlesinger and Bernhardt 2013), and combustion of these N pools and the acceleration of N cycling processes increases nutrient leaching following fire (Chorover and others 1994; Murphy and others 2006). Oxidation of forest biomass, litter, and soil organic matter commonly increases soil ammonium availability and nitrification for months to several years following wildfire or slash burning (Wan and others 2001; Rhoades and others 2015). Accumulation of stable pyrogenic C in soils (DeLuca and others 2006) and changes in soil ammonium and pH (Hanan and others 2016) can have decades-long effects on soil nitrate availability. In conjunction with decreased plant nutrient demand and altered litter N inputs, the persistent, elevated streamwater N losses we observed in extensively burned catchments are the likely product of higher soil N turnover and leaching from burned uplands.

The pattern of high DOC export from catchments with a low extent of wildfire is the result of both quantitative and qualitative post-fire change. By definition, the majority of organic matter and C is removed from high-severity areas by wildfire combustion and erosion (Keeley 2009; Homann and others 2011). In contrast, areas with moderate-severity wildfire lose less C and retain a variety of organic matter sources, including live and dead vegetation, and unburned and charred wood and

soil O horizons. The DOC leached from burned soils is affected by both the variety of organic matter types remaining after the fire (Chow and others 2009) and alterations during combustion. For example, forest biomass burned at moderate temperature ($\sim 250^{\circ}$C) produced more DOC with proportionally higher aromatic content (Wang and others 2015; Cawley and others 2017) than biomass burned at higher temperatures.

In addition to reduced soil nutrient uptake (Certini 2005), the slow recovery of riparian vegetation (Figure 5) has implications for stream light, temperature (Figure 6), and organic matter inputs and possible effects on in-stream metabolism and nutrient demand (Betts and Jones 2009). Streams draining catchments with extensive wildfire had much lower DOC:TDN relative to unburned catchments (18 vs. 8 in unburned vs high burn extent). The high inorganic N and low DOC we measured in extensively burned catchments may indicate that severe wildfire shifts the stoichiometric constraints on stream productivity. Indeed, preliminary findings from assessments of stream metabolism and in-stream production show that streams in burned catchments maintain high levels of gross and net primary production and that N limitations on autotrophic production are relaxed (A. Rhea, unpublished data). Our ongoing work will evaluate potential changes in C or P limitations in the N-enriched burned streams.

Elevated post-fire N and C export from headwater catchments have obvious consequences for drinking water supply, municipal water treatment, and aquatic habitat, yet they also underscore the prolonged response to severe wildfire. It is unknown whether the continued nutrient losses in catchments burned by the Hayman Fire are the consequence of lasting changes in soil nutrient availability and leaching (Certini 2005; Turner and others 2007; Jiménez-Esquilín and others 2008), or merely because nutrient supply remains higher than plant demand. In forests near the Hayman Fire (Boyden and Binkley 2016) and temperate forests elsewhere, low soil N supply constrains tree growth, so N losses associated with the fire are likely to exacerbate forest nutrient limitations. Ongoing upland reforestation will compensate for slow tree establishment in severely burned areas (Chambers and others 2016) and facilitate recovery of numerous ecosystem processes and conditions. Our findings suggest that targeting tree planting activities at exposed headwater riparian zones may accelerate the return to pre-fire nutrient retention and stream nutrient levels.

Ecosystem Recovery

Catchment-scale nutrient demand may remain depressed until upland and riparian vegetation regain pre-fire canopy cover and aboveground biomass. After the Hayman Fire, herbaceous plant cover increased rapidly and surpassed pre-fire levels within about 5 years (Fornwalt and Kaufmann 2014; Abella and Fornwalt 2015; Fornwalt and others 2018). This post-fire plant response would have increased infiltration and reduced overland flow (Pannkuk and Robichaud 2003) and is likely to explain the declines in stream turbidity and TSS we observed. The persistent post-fire stream nitrate response, in contrast, may be the consequence of the slow pace of upland and riparian forest recovery after the burn (Chambers and others 2016; Wang and Zhang 2017). Tree establishment has been rare within high-severity burn patches, for both the Hayman Fire and other Colorado fires in ponderosa pine forests (Chambers and others 2016). Our estimate that forest recovery to pre-fire conditions may require ~ 35 years (Figure 6) agrees with these field observations and is within the 20–50-year timeframe proposed by others for the Hayman Fire (Wang and Zhang 2017).

The Hayman Fire provides an example of potential impacts of changing climate on forested catchments and of the effects of long-term land use practices on wildfire behavior. Similar to forests across western North America, a century of fire suppression increased the density of trees and fuel loads in Front Range ponderosa pine forests (Sherriff and others 2006; Chambers and others 2016). Coupled with observed trends in fire season length, and fire size and severity (Westerling and others 2006; Miller and others 2009), these changes create additional uncertainty about ecosystem resilience and forest structure and composition under future climate conditions (Millar and Stephenson 2015). For example, recent studies suggest that projected increases in drought and associated wildfires may have negative consequences for tree regeneration in a number of western forest types (Savage and others 2013; Harvey and others 2016; Stevens-Rumann and others 2017). Our NDVI analysis (Figure 5) suggests that another 20 years may be required for vegetation to recover to pre-fire levels, though repeat sampling within high-severity patches within the Hayman Fire indicated that trees or shrubs may not return to pre-fire densities in some locations (Fornwalt and others 2018). Tree regeneration within the large patches of high-severity wildfire

has created a clustered distribution of ponderosa pine that corresponds to location of surviving mature trees (Chambers and others 2016; Malone and others 2018). This irregular spatial pattern is similar to the historic forest structure thought to have occurred prior to the era of fire suppression (Kaufmann and others 2000; Brown and others 2015). In fact, development of this pattern is a goal of management aimed at creating forest structure consistent with the frequent, low-severity surface fires that were typical prior to fire suppression (Larson and Churchill 2012; Underhill and other 2014; Addington and others 2018).

The persistent post-fire stream N and C changes we report offer one example of how a 'mega disturbance' (Millar and Stephenson 2015) may alter ecosystem structure and resilience (Westerling and others 2011; Beck and others 2018) and processes such as nutrient retention in dry conifer forests. It seems likely that forest change following extensive, high-severity wildfire will have novel biogeochemical outcomes for streamwater quality and watershed ecology and nutrient retention (Gundale and others 2005). Ecosystem outcomes after individual disturbances are the unique combinations of site conditions, disturbance characteristics, and post-disturbance interactions (Turner 2010). Unknowns regarding the timing and spatial pattern of post-fire forest recovery remain, and the value of pre-fire conditions as a biogeochemical and ecological reference is uncertain. In addition to other sources of disturbance, forests of the Colorado Front Range, like elsewhere in the continental USA, are subject to increased amounts of N deposition associated with urban growth, agricultural production, and other factors (Vitousek and others 1997; Fenn and others 2003; Galloway and others 2003). Our findings coupled with the increasing frequency and severity of wildfire (Abatzoglou and Williams 2016; Westerling and others 2006) and elevated N deposition demonstrate the potential for substantial post-wildfire changes in N retention that have implications for nutrient export and delivery of clean water from headwater forests (Emelko and others 2011; Brown and Froemke 2012; Bladon and others 2014).

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