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Effects of 2003 wildfires on stream chemistry in Glacier National Park, Montana[†]

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Abstract:

Changes in stream chemistry were studied for 4 years following large wildfires that burned in Glacier National Park during the summer of 2003. Burned and unburned drainages were monitored from December 2003 through August 2007 for streamflow, major constituents, nutrients, and suspended sediment following the fires. Stream-water nitrate concentrations showed the greatest response to fire, increasing up to tenfold above those in the unburned drainage just prior to the first post-fire snowmelt season. Concentrations in winter base flow remained elevated during the entire study period, whereas concentrations during the growing season returned to background levels after two snowmelt seasons. Annual export of total nitrogen from the burned drainage ranged from 1·53 to 3·23 kg ha^{-1} yr^{-1} compared with 1·01 to 1·39 kg ha^{-1} yr^{-1} from the unburned drainage and exceeded atmospheric inputs for the first two post-fire water years. Fire appeared to have minimal long-term effects on other nutrients, dissolved organic carbon, and major constituents with the exception of sulfate and chloride, which showed increased concentrations for 2 years following the fire. There was little evidence that fire affected suspended-sediment concentrations in the burned drainage. Sediment yields in subalpine streams may be less affected by fire than in lower elevation streams because of the slow release rate of water during spring snowmelt. Published in 2008 by John Wiley & Sons, Ltd.

KEY WORDS stream chemistry; wildfire; nitrogen; nutrient fluxes; snowmelt; Rocky Mountains

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INTRODUCTION

Wildfires burned nearly 700 km^2 in Glacier National Park (GNP) during summer 2003, more than 30 times the annual average. Climate change (Saunders *et al*., 2008), decades of fire suppression (Spencer *et al*., 2003), and long fire return intervals (Barrett, 2004) may have contributed to the severity of fires during 2003. Increased concern over the risk of high-severity fires has prompted resource managers to reevaluate current fire-management policies. An important concern for fire management is the effect of fires on aquatic ecosystems and, in particular, the effects on water quality. Fire-related changes that affect water quality include burning of vegetation and litter, which releases nutrients and metals; heating of soils, which alters soil properties and flow paths; and post-fire erosion, which increases turbidity and sediment loads (Martin *et al*., 2000). Post-fire effects on water quality can be highly variable depending on factors such as hydrologic regime, topography and geology, and fire size and intensity (Ranalli, 2004). Relatively few studies of post-fire water quality in the Northern Rocky Mountains have been conducted, particularly in the snowmelt-dominated subalpine ecosystems that are common to GNP. Stream nutrient transport in GNP was studied by Spencer and Hauer (1991) and Hauer and Spencer (1998) during and following the Red Bench Fire in 1988. Water-quality effects of the 1988 wildfires in Yellowstone National Park, Wyoming were reported by Lathrop (1994), Ewing (1996), and Gerla and Galloway (1998). Minshall *et al*. (2001) studied post-fire water quality and biotic responses of snowmelt-dominated streams in central Idaho following the Mortar Creek Fire in 1979. Runoff and sedimentation rates in montane forests in west-central Montana were studied following the Valley Complex Fires in 2000 (Spigel and Robichaud, 2007).

The objective of this study was to determine the effects of moderate- to high-intensity wildfires on stream chemistry in GNP. We examined seasonal and temporal trends in concentrations and fluxes of major constituents, nutrients, and suspended sediment in two study areas in the park for a 4-year period following the 2003 fires.

MATERIALS AND METHODS

Study Area Description

The study area is on the west side of GNP, which is located in the northern Rocky Mountains in north-western Montana (Figure 1). GNP is characterized by rugged, mountainous terrain spanning an elevation range of 950 to 3100 m. Bedrock is Proterozoic Belt Supergroup consisting of thick sequences of argillite, quartzite, and carbonate rocks (Ross, 1959). The west side of the park has a semi-maritime climate characterized by cool, wet winters and mild, dry summers. More than one-half of the annual precipitation falls as snow and accumulates in a seasonal snowpack between November and April

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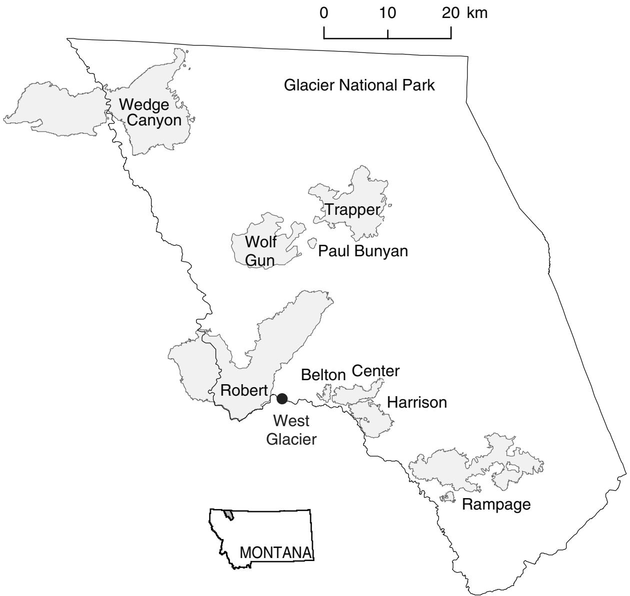

Base from U.S. Geological Survey digital data, 1:100,000

Figure 1. Location of 2003 wildfires in Glacier National Park, Montana

(Finklin, 1986). Most of the study area is within the subalpine zone (1800–2700 m), which is dominated by cool, moist coniferous forests of subalpine fir, Douglas fir, and Engelmann spruce (Habeck, 1987). Areas below 1800 m are in the montane zone where vegetation is predominantly Douglas fir, grand fir, western larch, western red cedar, and western hemlock.

During the summer of 2003, nine wildfires burned nearly 700 km^2 in and adjacent to GNP (Figure 1). Fire locations, sizes, and burn intensities were determined from NPS GIS coverages (http://nrdata.nps.gov/GLAC/-glacdata/NRdata/fire/) derived from Landsat data (http://-burnseverity.cr.usgs.gov/fire_main.asp) (Table I). This study was conducted in areas burned by the Robert, Trapper, and Rampage Fires. The Robert Fire, which was the largest of the 2003 wildfires, started on 23 July 2003 by a campfire, and burned 213 km^2 on the west side of the park. The fire was particularly intense on hillslopes along the north-east shore of Lake McDonald (Figure 2). Lake McDonald is the park's largest lake with a surface area of 2·78 km^2 and maximum depth of 486 m (Hauer

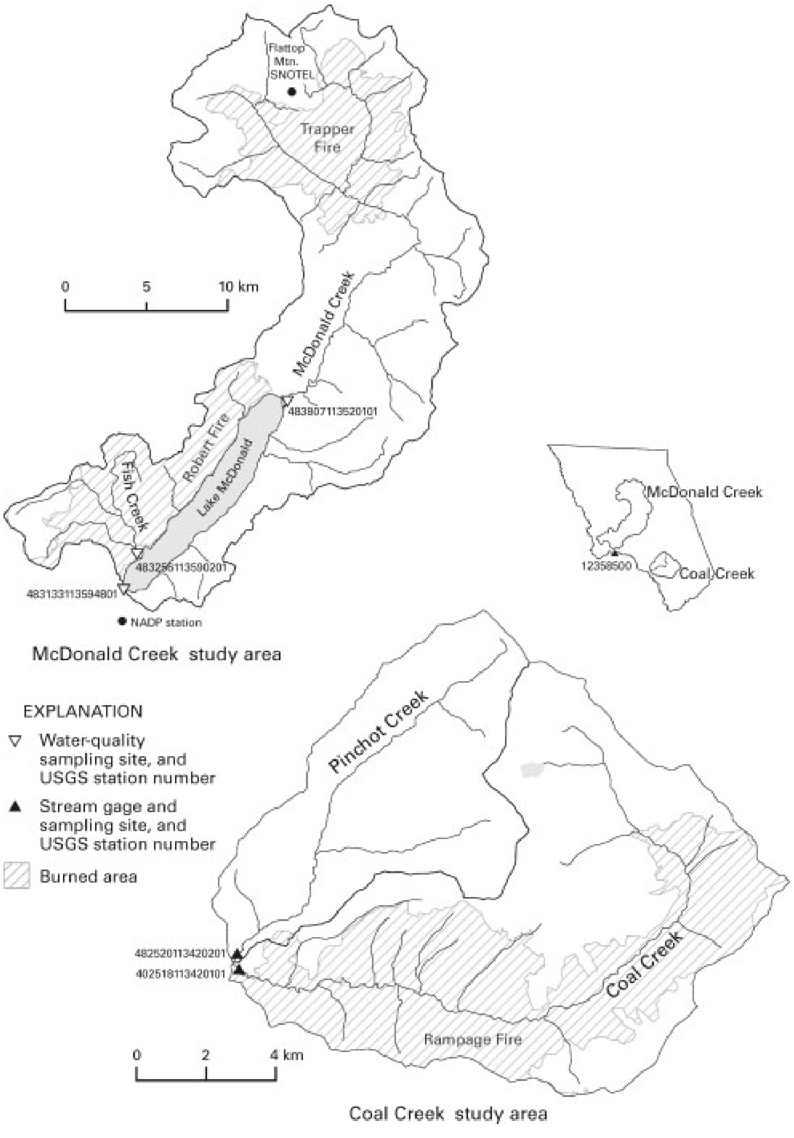

Figure 2. Maps showing locations of sampling sites in the Coal Creek and McDonald Creek study areas

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Table I. Characteristics of study sites in Glacier National Park

Stream drainage	Basin area (km^2)	Min. elev. (m)	Max. elev. (m)	Mean slope (%)	Forest cover (%)	Burned area (%)	Fire Name	Burn severity % low	% med	% high
				Coal Creek study area						
Coal Creek	96·4	1096	2898	27	73	51	Rampage	17	44	39
Pinchot Creek	47·3	1096	3084	31	62	0·4	unburned	—	—	—
				McDonald Creek study area						
Fish Creek	42·6	974	2022	14	93	73	Robert	16	52	32
McDonald Creek (above)	282	975	2913	24	58	26	Trapper	24	48	28
McDonald Creek (below)	450	961	2913	21	65	30	Robert, Trapper	18	49	33

et al., 2003). The Trapper Creek Fire was a medium- to high-severity fire that was started by lightning on 16 July 2003, and burned 75 km^2 in the headwaters of the McDonald Creek drainage. The Rampage Fire was started by lightning on 19 August 2003, and burned 87 km^2 in the south-west part of the park. The fire was particularly intense in the Coal Creek drainage, where it produced large areas of high-severity burns. All three of the fires were extinguished by rains near the end of October.

Water-quality sampling was initiated at two sites in the Coal Creek study area, Coal Creek (USGS station 482518113420101) and Pinchot Creek (USGS station 482520113420201), in December 2003, just prior to the 2004 snowmelt period (Figure 2). More than one-half of the Coal Creek drainage was burned by the Rampage Fire while the Pinchot drainage remained largely ($<0{\cdot}5\%$) unburned (Table I). Small areas in the lower part of both drainages were burned by the Crystal Creek Fire in 1984.

Water samples were also collected at three sites in the McDonald Creek study area, including one site on Fish Creek tributary (USGS station 483256113590201) and two on McDonald Creek, upstream (USGS station 483807113520101) and downstream (USGS station 483133113594801) from Lake McDonald (Figure 2). Due to funding constraints, sampling at these three sites could not be initiated until just prior to the onset of the 2005 snowmelt period. No unburned drainages were sampled in this study area; however, pre-fire water-quality data are available for all three sampling sites (Hauer *et al.*, 2003). More than 70% of the Fish Creek drainage was burned by the Robert Fire. In the McDonald Creek drainage, 16% was burned in headwater areas by the Trapper Fire and 14% was burned along the northwest side of the lake by the Robert Fire. A 35-km^2 area in the headwaters of McDonald Creek also burned in 1998.

Stream sampling

Stage was monitored at Pinchot Creek and Coal Creek with a pressure transducer and recorded every 15 min using a data logger. Rating curves were developed for each station by making manual discharge measurements with an acoustic Doppler velocity meter throughout the study period according to USGS methods (http://pubs.usgs.gov/twri/twri3a8/). Some periods of record had to be estimated due to missing data or ice-affected records. Estimations were made by simple correlation of daily streamflow between the study drainages and nearby gauged streams. The monitoring equipment at Pinchot Creek was destroyed by a storm in November 2006 so discharge was not measured at this site during the last year of the study.

More than 200 water-quality samples were collected at the two sites in the Coal Creek study area between December 2003 and August 2007. Samples were collected at least monthly but as frequently as twice weekly during the spring snowmelt period. More than 130 water-quality samples were collected at the three sites in the McDonald Creek study area between December 2005 and August 2007. Samples at these sites were collected bimonthly during snowmelt and monthly during other times of the year.

Grab samples were collected in 1 L polyethylene bottles and transported to the laboratory where they were filtered within 24 h of collection through a 0·45 μm capsule filter using a peristaltic pump. At Coal Creek and Pinchot Creek, automatic water samplers were deployed during high-flow periods to collect samples as frequently as every 3 days. Due to limited access to the study sites during high flow, samples sometimes sat unfiltered in the autosampler carousel for as long as 3 weeks prior to filtration. To test the effect of holding time in the autosampler, several replicate samples were collected; one sample was filtered immediately, and the other was left in the autosampler for various lengths of time. There was no difference in chemistry between the replicate samples except for higher ammonium concentrations (up to 0·1 mg L^{-1} as N) in the samples held in the autosampler. Because the concentrations increased with holding time, it was suspected that dissolved and/or particulate organic nitrogen was converted to ammonium by microorganisms during storage in the autosampler carousel. Nitrate concentrations were not affected by storage in the autosampler, indicating the ammonium was not subsequently converted to nitrate.

Analytical methods

Specific conductance and pH were measured in the laboratory on filtered sample aliquots. Chloride, nitrate, sulfate, and ammonium were determined by ion chromatography on filtered, chilled sample aliquots. Calcium, magnesium, sodium, potassium, and silica were analyzed by ICP–AES on filtered acidified (0·5% HNO_3) aliquots. Dissolved organic carbon (DOC) was analysed by persulfate oxidation and infrared spectrometry, and alkalinity was determined by Gran titration. Total nitrogen (N) and total phosphorus (P) were analysed using alkaline persulfate digestion and colorimetry on chilled, acidified unfiltered aliquots. Suspended sediment was determined gravimetrically on an additional 1 L sample collected at each site. Analyses were conducted at approved USGS laboratories using published analytical methods (http://bqs.usgs.gov/lep/index.html) and water-quality results are available from the USGS National Water Information System (NWIS) database (http://waterdata.usgs.gov/nwis).

RESULTS

Hydrologic conditions

The longest discharge record available for the area is from the USGS streamflow-gauging station on the Middle Fork of the Flathead River (station 12358500) near West Glacier (Figure 2). The Middle Fork streamflow-gaging station is approximately 22 km north-west of the Coal Creek study area and 4 km south of the Lake McDonald outflow. Streamflow in the Middle Fork is dominated by spring snowmelt with nearly 60% of the annual runoff occurring during May and June. Average annual runoff during water years 1971–2000 (October 1 to September 30) was 88 cm compared to average annual precipitation of 126 cm for the same period determined from the 400-m PRISM climate grids (http://prism.oregonstate.edu/). Over the 4-year study period, annual runoff for the Middle Fork was slightly below average in water years 2004 (84%), 2005 (86%), and 2007 (92%) and slightly above average in 2006 (107%) (http://waterdata.usgs.gov/nwis).

Mean daily streamflows for Coal Creek during the study period indicate that the timing of snowmelt runoff was similar among years (Figure 3). By contrast, streamflow patterns in fall and early winter showed considerable variability reflecting the frequency of late-season rain events. Annual precipitation and runoff during the study period were computed for Coal Creek, Pinchot Creek, and the Middle Fork of the Flathead River (Table II). Annual precipitation amount was estimated from the 400 m PRISM precipitation grid combined with measured precipitation at the Flattop Mountain SNOTEL station (http://www.wcc.nrcs.usda.gov/snow/) (Figure 2). Because the stream gauges were not installed until December 2003, discharge for Coal Creek and Pinchot Creek had to be estimated for the period 1 October to 20 December 2003. Estimates were based on daily discharge from the Middle Fork of the Flathead River, which remained very low in the months following the fire and accounted for only 5% of the annual runoff for water year 2004. Estimated annual precipitation was fairly consistent over the study period but was slightly higher in Pinchot Creek than Coal Creek due to differences in elevation between the two drainages (Table II). Runoff in Coal Creek was similar to the Middle Fork with the exception of 2005, when runoff was about 25% higher in Coal Creek. Pinchot Creek (unburned) showed a similar pattern; in 2005 the Pinchot to Middle Fork runoff ratio was about 20% higher than in other years of the study.

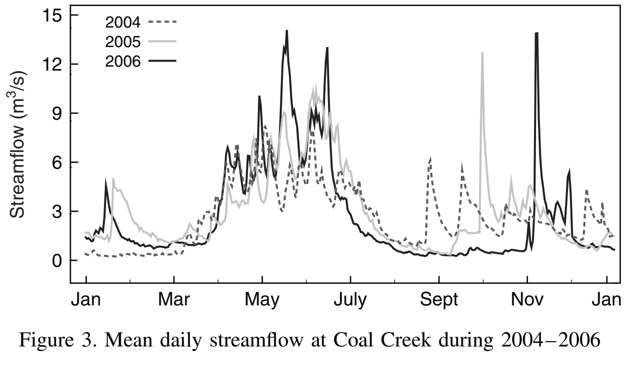

Figure 3. Mean daily streamflow at Coal Creek during 2004–2006

Table II. Annual precipitation and runoff during the study period for Coal Creek, Pinchot Creek, and the Middle Fork of the Flathead River near West Glacier

Water year	Annual precipitation (cm) Coal	Pinchot	Middle Fork	Annual runoff (cm) Coal	Pinchot	Middle Fork
2004	135	149	128	74[a]	98[a]	74
2005	124	136	117	95	115	76
2006	139	153	132	94	117	94
2007	142	156	134	76	—	81

[a] Discharge estimated for 1 October to 20 December based on daily discharge at Middle Fork Flathead River

Coal Creek study area

After the 2003 fires, stream-water nitrate concentrations increased in burned areas relative to unburned areas. Nitrate concentrations were more than 10 times higher in Coal Creek (burned) than in Pinchot Creek (unburned) during the first year following the fire, and concentrations exceeded 0·8 mg L^{-1} (Figure 4). Nitrate concentrations showed strong seasonality in Coal Creek, increasing through the winter months with concentrations peaking just before the onset of snowmelt. During snowmelt, concentrations dropped nearly fivefold due to snowmelt dilution and reached their lowest concentrations in mid- to late summer when biological demand was highest. Pinchot Creek also showed seasonality in nitrate, although the pattern was slightly different with concentrations peaking closer to the time of maximum streamflow due to preferential elution from the snowpack and flushing of soils by snowmelt (Campbell *et al.*, 1995). Winter nitrate concentrations in Coal Creek decreased by more than fourfold during the study period, but concentrations were still elevated relative to Pinchot Creek more than 4 years after the fire. Nitrate concentrations in Coal Creek during the growing-season (June–September) also showed a progressive decline, returning to near background levels by the end of 2006. Comparison of total nitrogen concentrations with dissolved nitrate indicates that the fire did not have an appreciable effect on the form of nitrogen transported by these streams as more than 90% of total stream-water nitrogen was present as dissolved inorganic nitrogen (nitrate) in the burned and unburned drainages (Figure 5).

In contrast to nitrate (and total N), other nutrients measured during the study period (ammonium and total P) did not appear to be affected by the 2003 fire. Interpretation of the ammonium data was complicated by the increase in ammonium observed in unfiltered samples stored in the autosampler carousel between sampling trips. Excluding the autosamples, the majority of ammonium concentrations were at or below the laboratory reporting level (0·007 mg L^{-1} as N), indicating that fire had a minimal effect on stream-water ammonium. Total P concentrations ranged from <0·004 to 0·030 mg L^{-1} in Coal Creek and <0·004 to 0·354 mg L^{-1} in Pinchot Creek, although more than 85% of samples had concentrations at or below the reporting level (0·004 mg L^{-1} as P). During base-flow conditions, total P concentrations were below detection in both Coal Creek and Pinchot Creek. Spikes in total P concentrations were observed in both streams during snowmelt, likely reflecting periods of increased sediment transport. Detected concentrations during snowmelt were larger in Pinchot Creek (unburned) than Coal Creek (burned), which limits our interpretation of fire effects on total P in Coal Creek.

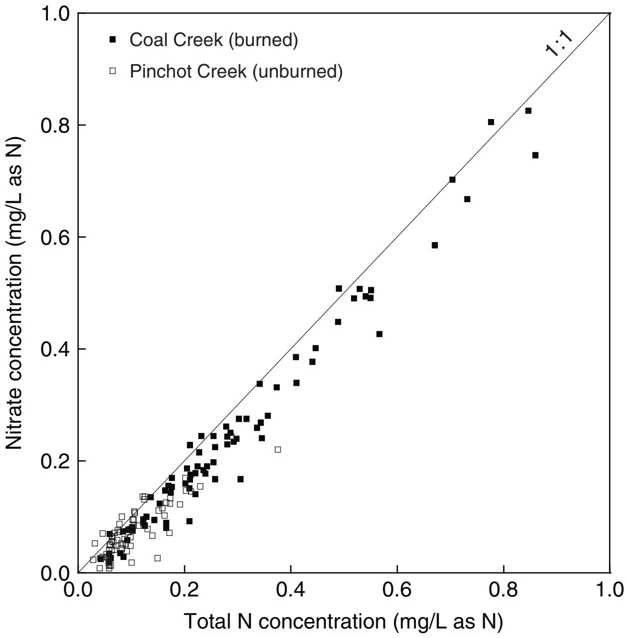

Figure 5. Comparison of stream-water nitrate and total nitrogen concentrations in the Coal Creek study area

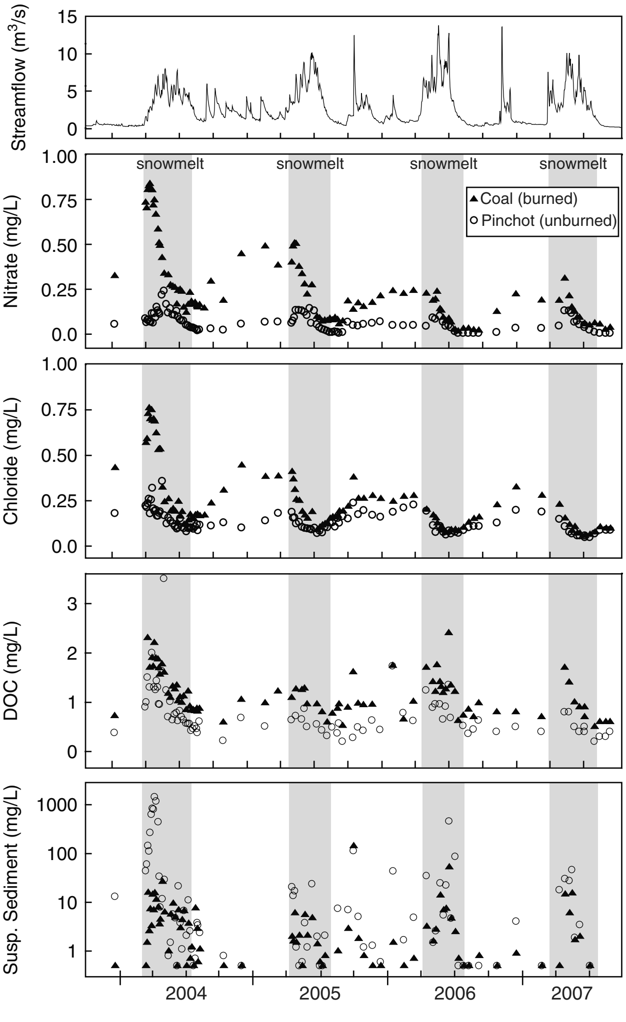

Figure 4. Stream-water chemistry in Coal Creek (burned) and Pinchot Creek (unburned) following the 2003 fires

Calcium, magnesium, and bicarbonate (based on alkalinity and pH) were the major dissolved constituents in both streams due to weathering of carbonate minerals in the underlying sedimentary rocks (Ross, 1959). Dissolved-solids concentrations in Pinchot Creek ranged from 33·8 to 91·2 mg L^{-1} and were nearly twice those in Coal Creek (range 20·6 to 49·4 mg L^{-1}), perhaps reflecting a greater percentage of carbonate units underlying the Pinchot drainage. Major constituent concentrations in both streams exhibited similar seasonal patterns with maximum concentrations during winter base-flow conditions and minimum concentrations just following peak snowmelt. The fire had little effect on major constituent concentrations with the exception of chloride and sulfate. Chloride concentrations were as much as four times higher in Coal Creek than Pinchot Creek during the first post-fire season, then returned to levels similar to Pinchot Creek by the end of the second year (Figure 4). Sulfate was as much as 2·7 times higher in Coal Creek during the first year but returned to concentrations similar to Pinchot Creek by the end of the first year. Similar to nitrate, the difference in concentration of chloride and sulfate in the burned and unburned drainages was greatest during winter base-flow conditions then concentrations converged in summer following the peak snowmelt period.

Other constituents measured during the study were DOC and suspended sediment (Figure 4). DOC concentrations ranged from 0·5 to 2·3 mg L^{-1} in Coal Creek and <0·2 to 3·5 mg L^{-1} in Pinchot Creek and were on average slightly higher in Coal Creek (mean 1·1 mg

L^{-1}) than Pinchot Creek (mean 0·7 mg L^{-1}). DOC concentrations showed similar seasonal patterns between the two streams and did not exhibit changes over the study period in Coal Creek indicating fire effects were minimal. Suspended-sediment concentrations in grab samples were highly variable and ranged from <0·5 to 147 mg L^{-1} in Coal Creek and <0·5 to 1497 mg L^{-1} in Pinchot Creek. Snowmelt typically produced the highest sediment concentrations, during which time concentrations in Pinchot Creek were as much as 100 times higher than in Coal Creek. Although the source of sediment in Pinchot Creek was not investigated as part of this study, high suspended-sediment concentrations are not uncommon for streams in GNP, particularly during snowmelt. This is illustrated in Figure 6 by a comparison of suspended-sediment concentrations in Coal Creek and Pinchot Creek with eight streams in other parts of the park sampled during a synoptic sampling campaign in May 2007 at peak flow and again in August during low flow (M.A. Mast, USGS, unpub. data, 2007).

Annual input from atmospheric deposition and streamwater export for total N and total P were calculated for the Coal Creek and Pinchot Creek drainage basins for the 4 water years following the fires (Table III). Total N inputs were estimated using the modelled precipitation (Table II) and concentrations data from the National Atmospheric Deposition Program (NADP) station (http://nadp.sws.uiuc.edu/) located near the south end of Lake McDonald (Figure 2). Total P inputs were not quantified because P species are not reported by NADP. Stream export was estimated by multiplying concentrations in stream samples by the total discharge between sampling dates centred on the day of sampling then summing results over each water year. Input and export results were normalized for drainage area and reported as kg ha^{-1} yr^{-1}. Total P concentrations in the stream samples were often below the laboratory reporting level of 0·004 mg L^{-1}. For these samples, we used uncensored values and replaced zero or negative values with 0·001 mg L^{-1}. Because of the large number of undetected concentrations, uncertainty associated with the estimates of total P export is greater than estimates of total N export.

Estimated inputs of total N to the study basins ranged from 1·9 to 2·6 kg ha^{-1} yr^{-1} and were slightly higher in Pinchot Creek compared to Coal Creek likely due to greater precipitation amount. Stream N export in Pinchot Creek ranged from 1·01 to 1·39 kg ha^{-1} yr^{-1}, which accounted for about one-half of the N inputs, indicating that the unburned drainage was a sink for inorganic nitrogen. Stream N export from Coal Creek ranged from 1·53 to 3·23 kg ha^{-1} yr^{-1} and exceeded export in Pinchot Creek in all years of the study. Stream N export from Coal Creek was highest in the 2 years following the fire and exceeded N inputs by 30% in 2004 and 70% in 2005. In 2006 and 2007, stream N export in Coal Creek fell below atmospheric input but was still elevated compared to Pinchot Creek. Annual total P export in Coal Creek ranged from 0·018 to 0·043 kg ha^{-1} yr^{-1} and was lower than total P export from Pinchot Creek, which likely reflects greater erosion rates in the Pinchot drainage. Field observations and suspended-sediment samples confirm

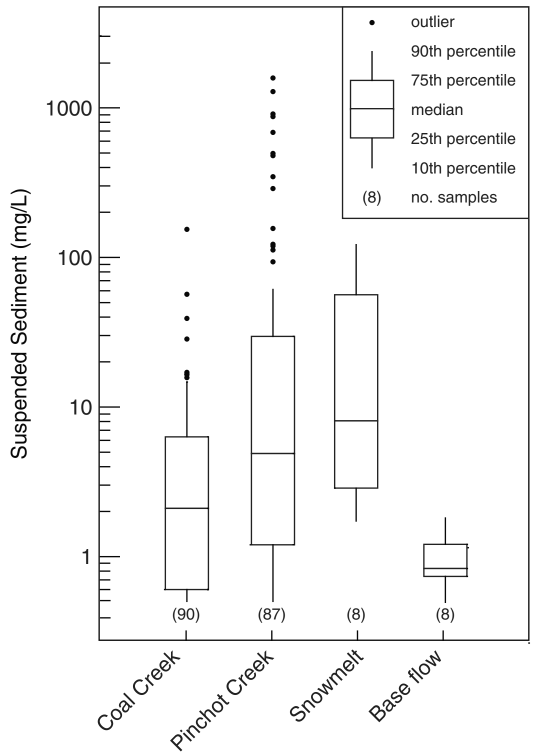

Figure 6. Suspended-sediment concentrations in Coal Creek and Pinchot Creek during the study period and eight other streams in GNP during snowmelt (May) and base flow (August) in 2007

Table III. Estimated water-year fluxes and volume-weighted mean (VWM) concentrations for total N and total P in Coal Creek and Pinchot Creek following the 2003 wildfires

	Total N						Total P			
	Input (kg ha^{-1})		Export (kg ha^{-1})		VWM (mg L^{-1})		Export (kg ha^{-1})		VWM (mg L^{-1})	
	Coal	Pinchot	Coal	Pinchot	Coal	Pinchot	Coal	Pinchot	Coal	Pinchot
2004	2·3	2·6	2·95	1·32	0·45	0·15	0·027	0·102	0·005	0·018
2005	1·9	2·1	3·23	1·39	0·31	0·12	0·043	0·237	0·004	0·019
2006	1·9	2·0	1·81	1·01	0·19	0·09	0·018	0·019	0·002	0·002
2007	2·3	2·6	1·53	1·24[a]	0·21	0·13	0·037	0·105[a]	0·007	0·011

[a] Based on a estimated runoff of 96 cm for Pinchot Creek in 2007.

that Pinchot Creek intermittently had very high sediment loads during snowmelt and storm events; however, the source of the sediment was not investigated.

McDonald Creek study area

Nitrate concentrations in the McDonald Creek study area showed only a minor response to the 2003 fire, probably because water samples were not collected until the second post-fire snowmelt season. Nitrate concentrations at all three sites were elevated in 2005 relative to 2007 during both spring snowmelt and summer base-flow conditions, although the effect was most pronounced at Fish Creek (Figure 7). For example, concentrations in Fish Creek peaked at 0·31 mg L^{-1} during the 2005 snowmelt period compared with 0·15 mg L^{-1} in 2007. Minimum summer concentrations in Fish Creek were 0·09 mg L^{-1} in 2005 and 0·03 mg L^{-1} in 2007. In McDonald Creek, snowmelt concentrations upstream and downstream from the lake were 0·60 and 0·32 mg L^{-1} in 2005 and 0·56 and 0·24 mg L^{-1} in 2007. Minimum summer concentrations upstream and downstream from the lake were 0·19 and 0·16 mg L^{-1} in 2005 compared with 0·10 and 0·13 mg L^{-1} in 2007. The ratio of nitrate to total N indicates most stream-water nitrogen was present as dissolved inorganic nitrogen. All three sites showed similar seasonal patterns in nitrate although the range of concentrations differed greatly among the sites. McDonald Creek upstream from the lake exhibited the widest range with concentrations decreasing nearly fivefold during spring snowmelt. The narrow range of concentrations at the site downstream from the lake reflects long hydrologic residence times of water in the lake. Similar to Coal Creek, fire had little effect on the other nutrients and major dissolved constituents with the exception of chloride and sulfate, which were elevated in 2005 relative to 2006 and 2007.

Pre-fire nutrient data are available for all three stream sites in the McDonald Creek study area. These sites were sampled between 1993 and 1998 as part of a study of stream-water nutrient dynamics and were analysed for nitrate, total N, orthophosphate, total P, and DOC (Hauer *et al.*, 2003). Pre-burn (1993–1998) and post-burn (2005–2007) nitrate concentrations for sites in the McDonald Creek study area are compared in Figure 8. For perspective, nitrate concentrations in Pinchot Creek (unburned) and Coal Creek (burned) also are included in the figure. Using the Wilcoxon rank-sum test, differences in nitrate were found to be statistically significant for Fish Creek ($P < 0{\cdot}001$) and McDonald Creek downstream from the lake ($P < 0{\cdot}001$), but not for the site upstream from the lake ($P = 0{\cdot}573$). Differences in nitrate concentrations between Pinchot Creek (unburned) and Coal Creek (burned) also were statistically different over the study period ($P < 0{\cdot}001$). Post-fire nitrate concentrations were lowest in Fish Creek and highest in McDonald Creek upstream from the lake despite the fact that the percentage of burned area was nearly three times greater in the Fish Creek drainage. The same pattern was evident in the pre-fire data indicating that factors other than fire are more important for controlling nitrogen concentrations in the upper part of this drainage basin. Fire appeared to have the greatest effect on nitrate in Fish Creek, which was on average 2·5 times higher than pre-fire levels. Although no difference was observed at McDonald Creek upstream from the lake, nitrate downstream from the lake was about 1·5 times higher than pre-burn levels, indicating that burned areas around the lake had a greater effect than those in the upper part of the drainage. Differences in pre- and post-fire total P concentrations were statistically different only for Fish Creek ($P < 0{\cdot}001$) and were slightly higher in the pre-fire samples. This result is opposite to most published studies, which report increases in post-fire P in streams (Ranalli, 2004).

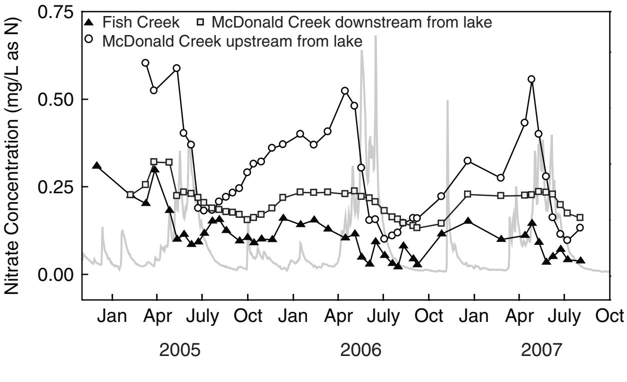

Figure 7. Stream-water nitrate concentrations in the McDonald Creek study area following the 2003 fires. Hydrograph for the Middle Fork Flathead River is shown in background to illustrate seasonal variation in streamflow

DISCUSSION

Previous studies report that annual runoff often increases in the first 1 or 2 years after burning (Helvey, 1980; Lavabre *et al.*, 1993; Moody and Martin, 2001; Inbar *et al.*, 1998; Fernández *et al.*, 2006). This change in

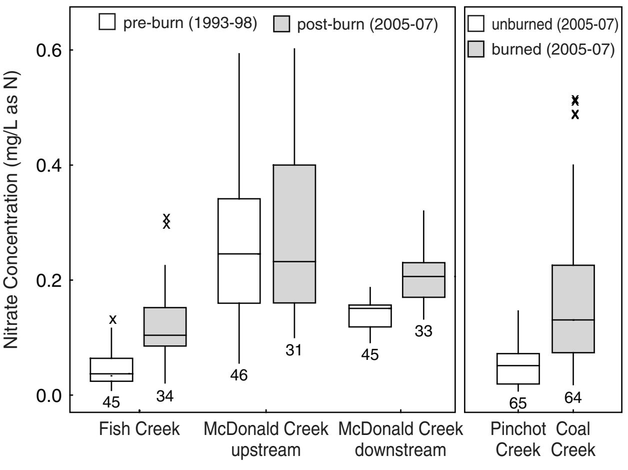

Figure 8. Comparison of pre-burn and post-burn nitrate concentrations for the three sampling sites in the McDonald Creek study area. Also shown are nitrate concentrations in the unburned (Pinchot Creek) and burned (Coal Creek) drainages in the Coal Creek study area for the same period of record

hydrologic response is primarily attributed to increased surface runoff caused by loss of vegetative cover and the greater water repellency of burned soils (Scott and Van Wyk, 1990; DeBano, 2000; Robichaud, 2000; Martin and Moody, 2001; Wondzell and King, 2003). Although 2005 runoff in Coal Creek was higher relative to the Middle Fork of the Flathead River, elevated runoff also was observed in Pinchot Creek (unburned) indicating that fire was not the cause of higher runoff in 2005 (Table II). The additional runoff in Coal Creek and Pinchot Creek primarily occurred during an exceptionally wet period in fall and early winter of 2004 and may reflect differences in runoff characteristics of these smaller drainage basins compared with the larger Middle Fork drainage basin. The apparent lack of post-fire response in annual runoff from Coal Creek may be explained by a combination of snowmelt hydrology and fire timing. Post-fire increases in runoff typically are most pronounced during short-duration high-intensity rain storms in summer that exceed soil infiltration rates and increase overland flow (Moody and Martin, 2001; Wondzell and King, 2003). Very little runoff occurred in the fall and winter months following the 2003 fires so the first major runoff event was spring snowmelt, which commenced in mid-March of 2004. During snowmelt, water is released over a longer duration and at a lower intensity compared to summer rain events, so there is less likelihood that infiltration rates will be exceeded (Huffman *et al.*, 2001). Other factors that could reduce the potential for post-fire increases in runoff at the study site include prevalence of frontal rain storms over convective storms during summer and fall and relatively high soil moisture due to the semi-maritime climate of the area (Wondzell and King, 2003).

The 2003 wildfires resulted in elevated stream-water nitrate concentrations and fluxes. Increases in stream-water nitrate are a commonly reported fire effect and generally are ascribed to the combination of reduced uptake by vegetation and increased soil nitrification of ammonium released during burning of organic matter (Ranalli, 2004; Certini, 2005). Nitrate concentrations in the burned drainage (Coal Creek) peaked in the first year following the fire then declined gradually over the next several years, which is a commonly observed temporal pattern in fire-affected streams (Gluns and Toews, 1989; Hauer and Spencer, 1998; Williams and Melack, 1997). On a seasonal basis, we observed the highest concentrations during winter base-flow conditions that declined markedly on the rising limb of the hydrograph due to snowmelt dilution. Because groundwater supplies most flow during winter, this pattern indicates that reduced uptake and (or) increased nitrification resulted in nitrate being leached from soils into the groundwater system. Our results contrast with other studies of snowmelt-dominated streams that report maximum nitrate concentrations during the rising limb or at the peak of the snowmelt hydrograph (Gluns and Toews, 1989; Hauer and Spencer, 1998; Bayley *et al.*, 1992; Minshall *et al.*, 2001), which typically is attributed to snowmelt flushing of soils. The reason for the different snowmelt response in Coal Creek is not clear but might be related to the effects of fire timing and intensity on the degree of nitrate leaching to ground water. Although nitrate concentrations remained elevated in winter baseflow 4 years after the fire, concentrations during summer low-flow conditions were only elevated for 2 years, presumably because uptake by vegetation increased enough to return concentrations to near background levels during the growing season.

On an annual basis, fire resulted in a net nitrogen export from the burned drainage for 2 years following the fire (Table III). Although stream export was still elevated relative to the unburned drainage in the third and fourth years of the study, export no longer exceeded atmospheric inputs. The magnitude of net losses in the first 2 years of the study was equivalent to atmospheric deposition of inorganic N during a single year. Post-fire losses of N by streams, however, are small compared to N losses due to volatilization during wildfires, which range from 100 to over 800 kg ha^{-1} yr^{-1} (Johnson *et al.*, 1998). Few studies have reported annual export of nitrate in stream water from burned areas, particularly for wildfires. In our study of a high-intensity wildfire, total N export (mostly as nitrate) in the burned drainage averaged 2·7 kg ha^{-1} yr^{-1} for the 3 years following the fire compared with 1·2 kg ha^{-1} yr^{-1} in the unburned drainage. Bayley *et al.* (1992) reported nitrate export ranging from 3·9 to 8·3 kg ha^{-1} yr^{-1} in moderate to high-intensity burned drainage basins in Ontario, Canada, in the first year after a fire, compared with background levels of 0·55 kg ha^{-1} yr^{-1}. In a Mediterranean pine and eucalyptus forest in Portugal, nitrate export of 2·5 kg ha^{-1} yr^{-1} was measured from a burned drainage, which was 250 times higher than export from an unburned drainage basin (Ferreira *et al.*, 2005). Slightly lower yields were reported for a prescribed burn in a forested drainage in the Sierra Nevada, where nitrate increased from 0·03 kg ha^{-1} yr^{-1} prior to the burn to 1·6 kg ha^{-1} yr^{-1} in the 3 years after (Williams and Melack, 1997). Extremely high nitrate export (16·8 kg ha^{-1} yr^{-1}) was reported following high-intensity prescribed burns in a southern California chaparral ecosystem, which was 40 times greater than export from unburned areas (Riggan *et al.*, 1994). The high export rates were attributed to chronic nitrogen enrichment of the ecosystem by atmospheric deposition.

Fire is not the only biochemical process resulting in nitrate export to streams within GNP. Results from the McDonald Creek study area reveal that nitrate concentrations in some unburned areas of the park were comparable with those measured in Coal Creek (Figure 8). The range of concentrations in unburned drainages was similar to those in high-elevation areas of the southern Rocky Mountains experiencing nitrogen saturation due to elevated rates of atmospheric deposition (Baron *et al.*, 2000; Williams and Tonnessen, 2000). Because deposition rates are relatively low in GNP, it is more likely that sources within the watershed are contributing to nitrate export in surface water. Hauer *et al.* (2007) suggested that elevated stream nitrate in McDonald Creek may be caused by the high density of alders in steep avalanche terrain, which increase the nitrogen content of soil through symbiotic nitrogen fixation. Alternatively, the underlying bedrock could be a source of N to streams, as has been documented for undisturbed watersheds in the Sierra Nevada dominated by metavolcanic and metasedimentary rocks (Holloway *et al.*, 1998).

In contrast to nitrate, fire appeared to have minimal effect on the other nutrients measured in stream water, which included ammonium and total P. Some studies have reported increased stream-water ammonium during the first few weeks or months following a fire, which is attributed to leaching of ammonium produced during burning of organic matter (Hauer and Spencer, 1998; Williams and Melack, 1997). Because sampling of Coal Creek was not initiated until 2 months after the fire was extinguished, it is possible that short-term effects on ammonium may have been missed in our study. Short-term effects on stream-water phosphorus (total and orthophosphate) are reported in the literature and generally are attributed to dissolution of ash deposited in or eroded into surface water (Ranalli, 2004). Similar to ammonium, short-term changes may have been missed during our study due to lack of samples in the weeks immediately following the fire. Moreover, total P concentrations in Pinchot Creek (unburned) were substantially larger than in Coal Creek during snowmelt and rain events, which also limits interpretation of our phosphorus data. In contrast to our study, wildfire caused substantial increases in ammonium and phosphorus concentrations in stream drainages in the north-western part of GNP burned by the Red Bench Fire in 1988 (Spencer and Hauer, 1991; Hauer and Spencer, 1998; Spencer *et al.*, 2003), but the effect was short-lived. In streams sampled while the fire was still burning, nutrient concentrations increased 5–60-fold, reaching maximum concentrations of $0{\cdot}26$ mg L^{-1} for ammonium and $0{\cdot}21$ mg L^{-1} for total P (Spencer and Hauer, 1991). Dissolution of smoke into surface water caused higher ammonium while aerial deposition of ash into streams caused elevated P (Spencer and Hauer, 1991). During the 5 years following the fire, ammonium showed differences between burned and unburned drainages only during the first spring runoff period (Hauer and Spencer, 1998). Total P concentrations appeared to show a response in some streams but not others. However, pre-fire data were not available, so the importance of other controls on phosphorus transport could not be evaluated.

Of the major dissolved constituents, fire effects in this study were detectable only for concentrations of sulfate and chloride, which both showed modest increases in the burned drainages during the first 2 years following the fire: the increases were most pronounced during winter base-flow conditions. Increases in water-extractable sulfate in soils and sulfate in soil solutions have been reported following fire (Murphy *et al.*, 2006). The increase is attributed to oxidation of sulfur in soil organic matter or the release of sulfate in plant litter tissue during the fire (Murphy *et al.*, 2006). Chloride is likely released from burning of plant tissue and is precipitated as soluble salts in the ash. Both chloride and sulfate are mobile anions that are subsequently leached from the soil surface by melting snow and rain to the underlying soil and eventually to the groundwater system and to streams (Ranalli, 2004). The lack of response for other major constituents probably reflects the high dissolved-solids concentrations that are characteristics of streams draining the carbonate-bearing bedrock, which may have masked any post-fire changes in concentration.

Suspended-sediment concentrations in Coal Creek did not change appreciably over the study period, indicating fire effects on sediment transport were minimal in this drainage basin. However, interpretation of fire effects on erosional processes was somewhat hindered by the fact that sedimentation rates were substantially higher in the unburned drainage than the burned drainage. Removal of vegetation and changes in soil properties are key factors controlling post-fire erosion rates (Shakesby and Doerr, 2006). A commonly reported fire-related change resulting in increased erosion rates is the formation of a water-repellent layer at the surface of burned soils (DeBano, 2000; Shakesby *et al.*, 2000). Huffman *et al.* (2001) suggested that during snowmelt, streams should be less affected by fire-induced water repellency because the slow rate of snowmelt causes a gradual increase in soil moisture. As burned soils begin to wet, there is usually a soil-moisture threshold at which they become hydrophilic, allowing meltwater to infiltrate readily into the soil (Doerr and Thomas, 2000; Huffman *et al.*, 2001). For burned areas in the Front Range of Colorado, less than 10% of post-fire sediment production occurred during frontal rainstorms and snowmelt between November and May (Benavides-Solorio and MacDonald, 2005). Another contributing factor may have been the timing of the 2003 fires. Time since burning has been shown to be a significant control on breakdown of soil-water repellency, particularly for high-intensity burns, although the effect is highly site-specific (MacDonald and Huffman, 2004). Based on discharge records from the Middle Fork of the Flathead River, there was minimal stormflow runoff between the time the fires were extinguished in late October and the onset of snowmelt in early April. During the several months the stream drainage remained snow covered with little hydrologic activity, the water repellency of burned soils may have started to weaken. As snowmelt commenced, soil moisture increased and water repellency likely continued to decline.

CONCLUSIONS AND IMPLICATIONS

Changes in stream chemistry were evaluated for 4 years following large wildfires that burned in GNP during 2003. These results will contribute to a growing body of knowledge on ecological effects of wildfire, which will aid land managers in reassessing and modifying fire and forest management policies for the future.

Moderate to intense wildfire resulted in modest increases in stream-water nitrate concentrations that persisted for several years after the fire. Interestingly, elevated nitrate concentrations were observed in some unburned areas of the park, indicating that other watershed processes can cause the same magnitude of nutrient loss to park streams. There is often concern that elevated nutrient export following fire has the potential to cause eutrophication in downstream rivers and lakes or to contaminate drinking-water supplies. Post-fire nitrate concentrations in our study were more than an order of magnitude below the US Environmental Protection Agency (EPA) drinking water standard (10 mg L^{-1}); however, concentrations from burned drainages seasonally exceeded the EPA-recommended nutrient criterion for total N (0·31 mg L^{-1}) in Ecoregion II (http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/index.html). The highest concentrations in burned drainages were observed during winter and probably were due to increased post-fire nitrification in soils followed by leaching to the ground-water system. Nitrate release during winter when biological activity is low may have little effect on productivity in rivers and streams. In downstream lakes and reservoirs, however, nitrate may accumulate during winter, resulting in increased productivity during the subsequent growing season. Moreover, ash deposited in the lake during and after the fire and subsequently incorporated into the lake sediment could release P to the water column that, coupled with additional nitrate loading from fire-affected streams, could lead to even greater changes in the trophic status of the lakes and reservoirs.

In contrast to nitrate, little evidence was found that wildfire had long-term effects on total P export in streams. Because P is strongly linked to sediment transport, this result is consistent with the lack of change in post-fire sedimentation rates in Coal Creek (the burned drainage). We suggest that sediment yields in subalpine streams such as Coal Creek may be minimally affected by fire because the slow release rate of water during snowmelt reduces the water repellency of burned soils. High sedimentation rates in Pinchot Creek (the unburned drainage) as well as other park streams indicates that variability caused by other factors may make it difficult to predict the effects of wildfire on erosional processes in the park.

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