Wildfire impacts on nitrogen concentration and production from headwater streams in southern Alberta's Rocky Mountains

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Abstract: The objective of this study was to examine initial effects of the 2003 Lost Creek wildfire (southwestern Rocky Mountains of Alberta) on concentrations and production (yield and total export) of several nitrogen (N) forms, and to explore initial recovery of these effects within the first 3 years after the fire. During the first postfire year, nitrate (NO_3^-), dissolved organic nitrogen (DON), and total nitrogen (TN) concentrations in severely burned watershed streams were 6.5, 4.1, and 5.3 times greater, respectively, than those in reference streams. Weaker effects were evident for concentrations of ammonium (NH_4^+; 1.5 times) and total particulate nitrogen (TPN; 3.0 times). A rapid decline in mean watershed concentrations and production of NO_3^-, DON, total dissolved nitrogen (TDN), and TN was observed from burned watersheds over the three seasons after the fire. However, elevated NO_3^-, TDN, and TN concentrations and production were still evident during the snowmelt freshet and following precipitation events after 3 years. Effects of the burn were strongly influenced by the regional flow regime, with the most elevated N concentrations and production occurring during higher discharge periods (snowmelt freshet and storm flows).

Résumé : Cette recherche avait pour objectif d'étudier les effets initiaux du feu de Lost Creek (Rocheuses du sud-est de l'Alberta) en 2003 sur la concentration et la production (production et exportation totale) de plusieurs formes d'azote (N) et d'explorer la récupération initiale à la suite de ces effets pendant les trois premières années après le feu. Durant la première année qui a suivi le feu, les concentrations de nitrate (NO_3^-), d'azote organique dissout (AOD) et d'azote total (AT) dans les ruisseaux des bassins sévèrement affectés par le feu étaient respectivement 6,5, 4,1 et 5,3 fois plus élevées que dans les ruisseaux témoins. Des effets plus faibles étaient évidents dans le cas des concentrations d'ammonium (NH_4^+; 1,5 fois) et d'azote total en particules (ATP; 3,0 fois). Une diminution rapide de la concentration et de la production moyennes de NO_3^-, d'AOD, d'azote total dissout (ATD) et d'AT a été observée dans les bassins affectés par le feu au cours des trois saisons qui ont suivi le feu. Cependant, une concentration et une production élevées de NO_3^-, d'ATD et d'AT étaient toujours évidentes lors de la crue causée par la fonte de la neige et à la suite d'événements de précipitation après trois ans. Les effets du feu étaient fortement influencés par le régime d'écoulement régional; la production et la concentration les plus élevées de N ont été observées durant les périodes de fort écoulement (crue causée par la fonte de la neige ou débits d'orage).

[Traduit par la Rédaction]

Introduction

Wildfires are the dominant natural disturbance in most Canadian forests (Van Wagner 1988), and the frequency of these disturbances has increased markedly in the past three decades (Stocks et al. 2003). This increase has been largely attributed to longer and warmer summers (Gillett et al. 2004), a phenomena that has been exacerbated by human-induced climate change (Intergovernmental Panel on Climate Change 2007). Current projections indicate that wildfire season length, fire severity, and the area burned in Canada will increase by ~74%–118% by the end of the century (Flannigan et al. 2005). The midelevation areas of the northern Rocky Mountains are one of the most vulnerable ecoregions in western North America, accounting for as much as 60% of the recent increases in large wildfires (Westerling et al. 2006). Critical to the biodiversity, ecological integrity, and economy of western North America (Hauer et al. 2007), the headwater streams in this subregion represent approximately 60% to 80% of total

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catchment stream length; generate the majority of streamflow in downstream reaches; and directly connect the upland and riparian landscape to downstream ecosystems (Freeman et al. 2007; MacDonald and Coe 2007).

The random character of wildfires usually precludes the design of tightly controlled watershed studies. Hence, relatively little research has been conducted on how wildfire affects a broad range of watershed functions compared with the number of studies of anthropogenic forest disturbances such as forest harvesting. The impacts of individual fires on the quality and quantity of water have been described in various forest regions, including eastern mixed hardwood–coniferous forests (Nelson et al. 2007), boreal shield (Bayley and Schindler 1991), western cordillera (Gluns and Toews 1989; Spencer and Hauer 1991; Brass et al. 1996; Minshall et al. 1997; Gerla and Galloway 1998; Moody and Martin 2001; Kunze and Stednick 2006), and high-precipitation coastal regions (Feller and Kimmins 1984; prescribed burning). Although the impacts of wildfire on watersheds vary depending on the extent and severity of the fire (Richter et al. 1982), few field studies have quantified the effects of wildfire severity and extent (proportion of watershed area) on watershed responses within, or across, the major hydroclimatic and physiographic settings of the forest regions in western North America. For example, while considerable wildfire–watershed research has been conducted within the western cordilleran region, the majority of these studies are from arid or semiarid montane settings and may not reflect the impacts of severe stand-replacing wildfire on watershed function in subhumid or humid regions of the Rocky Mountains.

While nitrogen (N) transport dynamics have been studied extensively in agricultural settings (e.g., Kemp and Dodds 2001; Follett and Delgado 2002) and following anthropogenic forest disturbances such as harvesting (e.g., Martin et al. 2000; Tetzlaff et al. 2007), less is known about the impact of wildfires on N loading. Elevated postfire N loading can influence ecosystem health, recreational use, and ease of treatment for potable water production (Ranalli 2004). In Rocky Mountain headwater streams, Hauer and Spencer (1998) reported elevated concentrations of dissolved and particulate N during the first year after a fire, with these concentrations declining rapidly during subsequent years. While similar temporal trends in recovery of postfire N concentrations have been reported in several studies, the magnitude of wildfire effects on N concentrations varies greatly (Gluns and Toews 1989; Minshall et al. 1997), and data from severe fires are particularly limited (Turner et al. 2007). Furthermore, only a few studies have concurrently measured nutrient concentration and streamflow (Gluns and Toews 1989; Minshall et al. 1997; Gerla and Galloway 1998; Hauer and Spencer 1998); accordingly, comprehensive analyses of the impacts of hydrologic regime on postfire N concentrations and total export variations in forest environments are sparse.

In the present investigation, a hydrometric and water-quality monitoring program was conducted in several high-water-yielding Rocky Mountain headwater watersheds in southern Alberta to quantify the initial magnitude of postfire changes in various N species and to describe the temporal trend of early N recovery in streams following a severe wildfire. Various N forms (nitrate (NO_3^-), ammonium (NH_4^+), dissolved organic N (DON), total dissolved N (TDN), total particulate N (TPN), and total N (TN)) and stream discharge were measured to describe the effect of wildfire on N concentrations, yields, and export during the dominant flow periods (base flow, storm flow, and snowmelt freshet) characteristic of the regional hydroclimatic setting.

Materials and methods

Study sites

The Lost Creek wildfire burned more than 21 000 ha in the Crowsnest Pass in the Rocky Mountain region of southwestern Alberta (49°37′N, 114°40′W) from July to September 2003. It was one of the most severe forest fires in the upper eastern slope forests of Alberta in many decades, burning the headwater regions of both the Castle and Crowsnest rivers (Fig. 1). These rivers form the headwaters of the Oldman River basin, which is one of Alberta's most stressed river systems from a regional water supply and demand perspective. The fire burned as a near contiguous crown fire and consumed virtually all forest cover and forest floor organic matter across a large proportion of the burned area.

Five study watersheds were instrumented in an area impacted by the 2003 Lost Creek wildfire that did not have significant historical logging disturbance. The study design consisted of three burned watersheds (Lynx Creek, Drum Creek, and South York Creek) and two unburned (reference) watersheds (Star Creek and North York Creek), instrumented during March to April 2004 (Fig. 1). All five watersheds have a north to north–east aspect. Four creeks drain into the Crowsnest River and one (Lynx Creek) drains into the Castle River. Study watersheds averaged 756 ha in size with a mean elevation (area weighted) of 1869 m. The area, elevation, and extent of burn in the study watersheds are presented in Table 1.

The study watersheds are characterized by Cretaceous shale and sandstone surficial geologic deposits overlain by well to imperfectly drained soils (Eutric or Dystric Brunisols). Soils have weak horizon development, characteristic of higher elevation northern environments. Before the fire, all of the watersheds were classified as montane ecozones dominated by Lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) at lower elevations, subalpine ecozones at midelevations dominated by Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), and alpine ecozones at higher elevations with alpine meadow vegetation and bare rock extending above treeline. In general, these alpine areas were not burned because of the absence of tree cover (fuel loading). Thus, virtually all of the forest cover was consumed in the wildfire, though the proportion of total watershed area burned in individual watersheds may be less than 100%.

Stream-water chemistry sampling

Beginning in April 2004, water-quality monitoring was conducted approximately every 10 days during snowmelt freshet, every 14 days after the freshet (i.e., ice-free periods), and every 1 to 2 months throughout winter. Additional

Fig. 1. Map of the Southern Rockies Watershed Project study area showing the 2003 Lost Creek fire boundary, streamflow gauging stations, meteorological stations, and research watersheds (from west to east: Star, North York, South York, Lynx, and Drum).

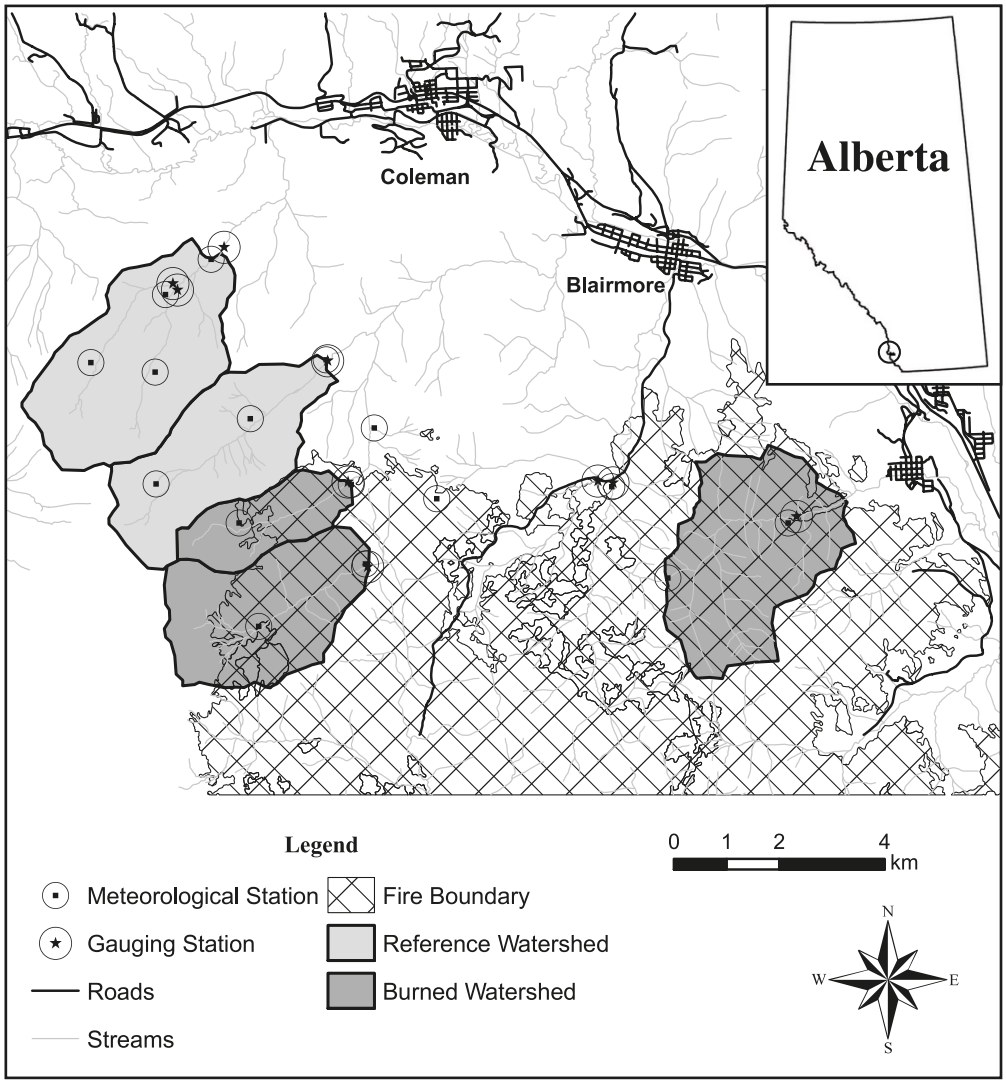


Table 1. The Southern Rockies Watershed Project catchment characteristics.

	Elevation (m)				Area burned	
Catchment	Mean	Min.	Max.	Total area (ha)	(ha)	(%)
Unburned (reference)						
Star	1851	1479	2627	1059	0	0.0
North York	1931	1562	2633	829	2	0.2
Burned						
South York	1971	1691	2635	359	191	53.3
Lynx	1906	1632	2629	821	553	67.3
Drum	1731	1432	2156	713	712	99.8

samples were collected during periodic storm events. Water samples were collected immediately upstream of hydrometric gauging stations in each of the five watersheds (Fig. 1). Manual depth-integrated water samples were collected in acid-washed (10% HCl) and triple-rinsed high-density polyethylene bottles, which were placed in a cooler. Samples were then refrigerated at 4 °C and transported to the laboratory for analyses within 4 days after collection.

Standard area–velocity current metering techniques using a Swoffer (Model 2100) velocity meter were used to measure instantaneous stream discharge. Staff gauges were used to simultaneously measure water levels to develop stage–

discharge relationships. To calculate continuous discharge at each of the gauging stations, continuous stage measurements were obtained using gas bubblers (Waterlog model H-350) or pressure transducers (Onset model U-20). A network of 15 meteorological stations provided distributed precipitation data across the five study watersheds. Discharge hydrographs and precipitation data were used to categorize regional streamflow regimes. These categories included (1) base flow or nonevent (summer and winter), (2) snowmelt freshet, and (3) storm flow, resulting from rainfall in each watershed.

Samples for water-quality analyses were collected concurrently with measurements of stream discharge. Nitrate (NO_3^-; 0.7 μm filter), TN (unfiltered), and TDN (0.45 μm filter) concentrations were determined by automated cadmium reduction (Method 4500; NO_3^-:F) using a Lachat QuikChem 8500 multichannel flow injection analyzer (Greenberg et al. 1999). TN and TDN samples were digested with potassium persulfate ($K_2S_2O_8$). NH_4^+ concentrations were determined by the standard automated phenate method (Method 4500; NH_3:H; 0.7 μm filter) (Greenberg et al. 1999). TPN was calculated as the difference between TN and TDN, dissolved inorganic nitrogen (DIN) was determined as the sum of NO_3^- and NH_4^+, and DON was calculated as the difference between TDN and DIN. Nutrient exports were calculated as the product of concentration and discharge, while specific yields (watershed area based), which refer to the quantity of nutrients passing a monitored stream cross section per unit area drained upstream of that cross section, were determined as the quotient of export divided by the watershed area.

Statistical analysis

While the lack of prewildfire data and the practical limitations to the number of burned and reference watersheds in research at this scale limit the possibility of broad spatial and temporal inferences, the interpretation of results and statistical analyses was approached cautiously (including the use of a significance threshold of $\alpha = 0.01$). All data analyses were performed with the SAS statistical package (Version 9.1, SAS Institute Inc., Carey, North Carolina).

The concentration, yield, and export data for the various N forms were not normally distributed (P–P plots, Q–Q plots, and Shapiro–Wilk test), as is typically the case for water-quality data. The data was also non-normally distributed after transformations by log, log(x + 1), or arcsine ($x^{0.5}$) to meet the assumption of normality necessary for using a parametric approach to statistical analysis. Nonparametric techniques such as Kruskal–Wallis are recommended for stream-water chemistry data, which typically does not meet assumptions for parametric methods (Helsel and Hirsch 2002). A series of single-factor Kruskal–Wallis tests and Dunn's mean comparison tests were used to analyze the effects of the "treatments" (reference and burned), flow regimes (base flow, storm flow, and snowmelt freshet), and time (years elapsed since the fire) on the concentration (micrograms per litre) of the various N species (NH_4^+, NO_3^-, DON, TDN, TPN, and TN).

The effect of higher streamflows (snowmelt freshet and storm flow) on N concentration and export was examined in burned and reference watersheds during the 2004 to 2006 period. Nitrogen–discharge relationships were developed using least-squares linear regression. These relationships were then compared using an overall test for coincidental regression (Zar 1999). Discharge and watershed area-weighted nutrient yields (kilograms per hectare per year) were used to compare changes in N yield between reference and burned watersheds.

Table 2. Annual precipitation (millimetres) in the study watersheds during 2004–2006.

	Year			
Catchment	2004	2005	2006	Mean
Unburned (reference)				
Star	816	951	979	915
North York	1276	1305	862	1148
Burned				
South York	762	1494	980	1079
Lynx	1027	1168	1076	1090
Drum	633	1045	712	797

Results

Precipitation and discharge

Annual precipitation during 2004 to 2006 (Table 2) ranged from 633 mm in Drum Creek watershed to 1494 mm in South York Creek. The highest annual precipitation occurred in the higher elevation Flathead Range watersheds (Star, North York, South York, and Lynx Creeks). The majority of snow fell from October to April, accounting for 50% to 70% of the total annual precipitation. The meteorological conditions varied considerably over the first three postfire growing seasons. The first postburn season of 2004 was cool and moist, but generally without large summer storm events (55% of days in growing season with 0.1–5 mm·day^{-1}). In 2005 several extremely large rainfall events in June (~150–175 mm of rain over 8 days) saturated soils and produced significant streamflow responses to smaller precipitation events throughout the remainder of the month. In contrast, the summer of 2006 was dry with no measurable precipitation observed from early June until late September.

Stream discharges were generally characteristic of high-water-yielding Rocky Mountain streams (Fig. 2). Snowmelt periods dominated the hydrologic regimes of all the watersheds. The highest streamflows typically occurred during spring snowmelt (mean daily discharges of ~5–10 mm·day^{-1}), extending from approximately mid-March until early June. All streams responded quickly to rainstorm events, with rapid time to rise and steep postpeak flow recession limbs evident in most of the storm hydrographs. Late summer and overwinter base flows were generally near 0.5–2 mm·day^{-1}. Periodic rain-on-snow or midwinter-melt events were a common occurrence, producing some of the more extreme flows, with daily mean discharges up to 28 mm·day^{-1} observed from 2004 to 2006. While the heavy rains in June 2005 produced very high discharges, no severe postfire flooding was observed during this series of events (second growing season after the wildfire).

Fig. 2. Mean daily concentrations for total particulate nitrogen (TPN), total dissolved nitrogen (TDN), and total nitrogen (TN), as well as streamflow (Q) in the reference and burned watersheds from 2004 to 2006. Note the different y-axis scales.

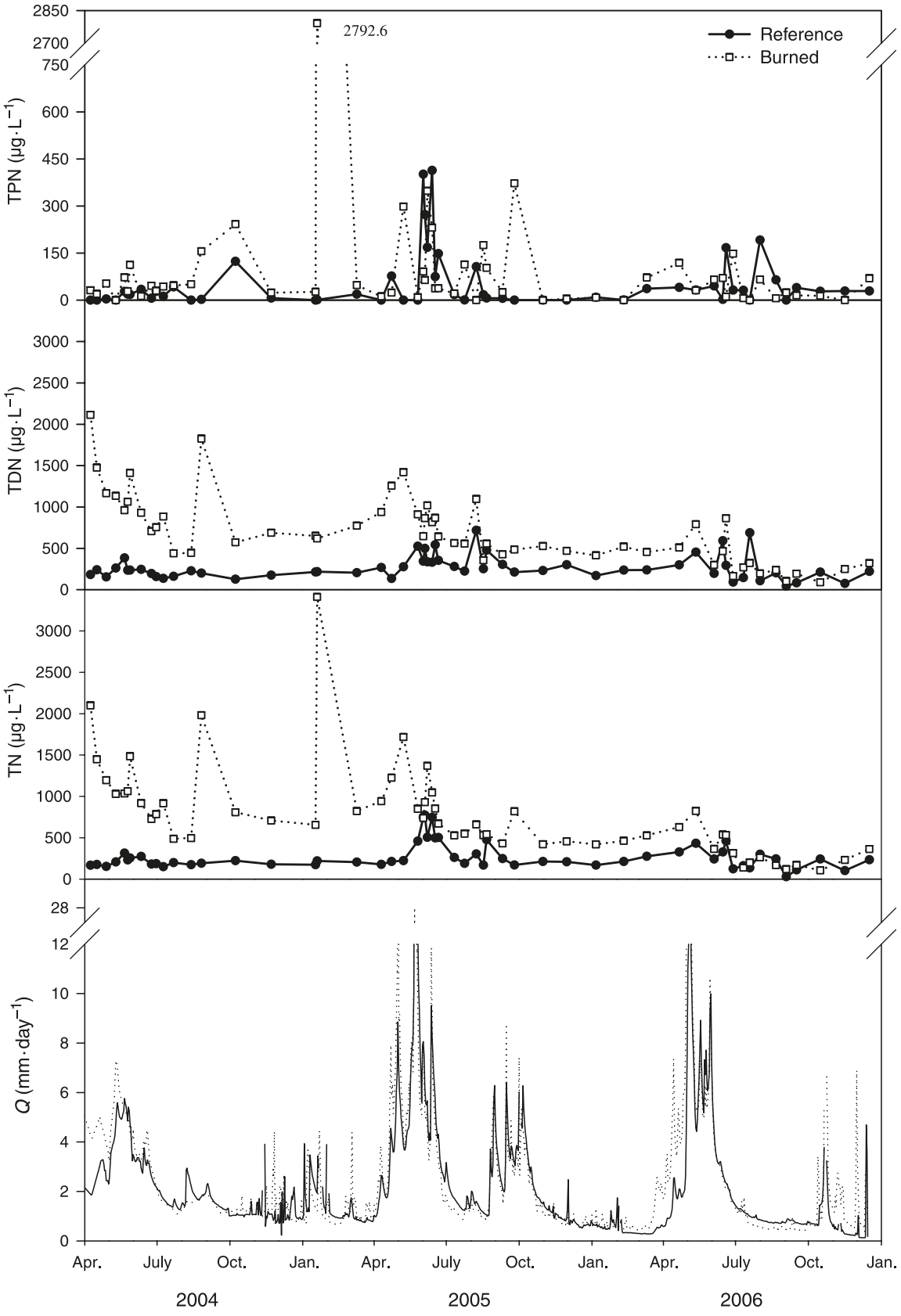


Table 3. Temporal distribution of events producing the highest total nitrogen (TN), dissolved organic nitrogen (DON), and dissolved inorganic nitrogen (DIN) concentrations (upper 10th percentile of all observations in 2004–2006; $n = 273$) in reference (unburned) and burned watersheds.

Nutrient	Year	Reference	Burned
TN	2004	0 (0%)	14 (50%)
	2005	1 (4%)	13 (46%)
	2006	0 (0%)	0 (0%)
DON	2004	0 (0%)	21 (75%)
	2005	1 (4%)	2 (7%)
	2006	2 (7%)	2 (7%)
DIN	2004	0 (0%)	12 (43%)
	2005	0 (0%)	16 (57%)
	2006	0 (0%)	0 (0%)

Note: Values indicate number of events (*n*), and percentage of total events in upper 10th percentile.

Stream-water chemistry

Concentrations of N species varied considerably with the extent of disturbance in the studied watersheds. Over the 3 year postfire period, reference streams had mean TN concentrations of 203.9, 349.0, and 229.7 $\mu g \cdot L^{-1}$ in 2004, 2005, and 2006, respectively. Streams in burned watersheds had significantly higher mean TN concentrations than reference streams ($p < 0.001$). Almost all of the highest TN concentrations (upper 10th percentile) occurred in burned watersheds during the first 2 years after the fire (Table 3). In all burned watersheds, mean TN decreased significantly from 2004 to 2006 ($p < 0.001$). During the first year after the fire, the mean TN concentration in streams draining burned watersheds (1074.0 $\mu g \cdot L^{-1}$) was 5.3 times greater than that in reference watersheds (Fig. 2). Over time, TN decreased in the burned watersheds to 916.9 $\mu g \cdot L^{-1}$ in 2005 (2.6 times greater than the reference) and 354.0 $\mu g \cdot L^{-1}$ in 2006 (1.5 times greater).

Differences in TDN concentrations between burned and unburned watersheds were comparable to those observed for TN because TDN accounted for the majority of TN (Table 4; Fig. 2). Relative to the reference watersheds, significantly higher TDN concentrations were observed in the burned watersheds ($p < 0.001$). In burned watersheds, significant decreases in TDN concentration over time were observed ($p < 0.001$). TDN decreased rapidly from a mean of 1036.2 $\mu g \cdot L^{-1}$ in 2004 to 748.8 $\mu g \cdot L^{-1}$ in 2005 and 359.6 $\mu g \cdot L^{-1}$ in 2006 (Fig. 2). Over that same period, reference streams had mean TDN concentrations of 208.1, 330.0, and 242.2 $\mu g \cdot L^{-1}$ in 2004, 2005, and 2006, respectively.

NO_3^- concentrations were also significantly higher in the burned watersheds than in the reference watersheds ($p < 0.001$; Fig. 3). In the reference streams, NO_3^- was relatively low, with mean concentrations of 76.4 $\mu g \cdot L^{-1}$ in 2004, 128.3 $\mu g \cdot L^{-1}$ in 2005, and 116.2 $\mu g \cdot L^{-1}$ in 2006. Comparatively, mean NO_3^- concentrations in streams from burned watersheds were 499.7, 536.2, and 239.7 $\mu g \cdot L^{-1}$ in 2004, 2005, and 2006, respectively. These mean annual values were 6.5, 4.2, and 2.1 times greater than those observed concurrently in reference streams.

Differences in mean NH_4^+ concentrations were observed between the burned and reference sites ($p < 0.01$), while time since the fire was also a significant factor ($p < 0.001$). The NH_4^+ concentration in all streams was generally low compared with the other N parameters measured, with mean concentrations in reference streams of 5.9 $\mu g \cdot L^{-1}$ (2004) and 3.0 $\mu g \cdot L^{-1}$ (2005 and 2006). Alternatively, the mean concentrations of NH_4^+ in burned streams were 8.9 $\mu g \cdot L^{-1}$ (2004), 9.4 $\mu g \cdot L^{-1}$ (2005), and 4.2 $\mu g \cdot L^{-1}$ (2006). The highest NH_4^+ concentrations coincided with the snowmelt freshet and major storm-flow events ($p < 0.001$). Multiple comparisons indicated that NH_4^+ concentrations during snowmelt were similar to those during storm-flow events ($p = 0.81$)

Streams in burned watersheds had higher mean DON concentrations than reference streams; however, the differences were not significant at $\alpha = 0.01$ ($p < 0.03$). The majority (75%) of the highest DON concentrations (upper 10th percentile) occurred in the burned watersheds during the first year after the fire (Table 3). Thus, time after the fire was a significant factor related to DON ($p < 0.001$). DON concentrations decreased rapidly in the burned streams from a mean of 528.0 $\mu g \cdot L^{-1}$ in 2004 to 203.8 $\mu g \cdot L^{-1}$ in 2005 and 125.1 $\mu g \cdot L^{-1}$ in 2006 (Fig. 3). In the reference streams, the mean concentrations of DON were 130.0 $\mu g \cdot L^{-1}$ in 2004, 198.7 $\mu g \cdot L^{-1}$ in 2005, and 132.0 $\mu g \cdot L^{-1}$ in 2006.

TPN concentrations were also higher in the burned watersheds than in the reference watersheds, but not at the threshold of $\alpha = 0.01$ ($p = 0.02$; Fig. 2). However, elevated TPN concentrations coincided significantly with storm-flow events ($p < 0.001$; Fig. 4). For example, the highest recorded TPN concentration during the study period was 2792.6 $\mu g \cdot L^{-1}$. This occurred on 19 January 2005 during a 3 day rain-on-snow event, with 136 mm of precipitation in addition to 25–50 mm of snowmelt. There was no relationship between TPN and time since the fire ($p = 0.74$).

Variation of all N species was strongly related to discharge across the range of streamflows that are characteristic of the study region ($p < 0.001$). Box-and-whisker plots (Fig. 4) of concentrations of NH_4^+, NO_3^-, DON, TPN, and TN separated by dominant flow period (base flow, snowmelt freshet, and storm flow) showed elevated concentrations during higher flow periods in the burned watersheds for all N species, except TPN during the snowmelt freshet. During base flow, only NO_3^- and TN concentrations were higher in the burned watersheds than in the reference watersheds ($p < 0.001$).

Mean separations tests revealed that the influence of the hydrologic regime on N export for all N forms, except TPN, did not differ between the snowmelt freshet and storm flow periods ($p = 0.29$ to 0.92; TPN, $p < 0.01$). Thus, snowmelt-freshet and storm-flow data were grouped to further assess the relationship between discharge (Q) and NO_3^-, DON, and TN export with time since the fire (Fig. 5). In the first postfire year, as Q increased, the rate of increase in each of these N forms was greater in burned than in reference watersheds. These differences were most pronounced in 2004 (first postfire season) and declined thereafter. Both TDN export ($p < 0.01$) and TN export ($p < 0.01$) in 2004 were strongly correlated with Q and were

Table 4. Mean nutrient yield (kilograms per hectare per year) and standard error (in parentheses) for ammonium (NH_4^+), nitrate (NO_3^-), dissolved organic nitrogen (DON), total particulate nitrogen (TPN), and total nitrogen (TN) from 2004 to 2006.

		Reference		Burned		
Nutrient	Year	Star	North York	South York	Lynx	Drum
NH_4^+	2004	0.04 (0.02)	0.08 (0.03)	0.14 (0.04)	0.15 (0.05)	0.06 (0.02)
	2005	0.03 (0.01)	0.08 (0.03)	0.16 (0.09)	0.09 (0.04)	0.45 (0.33)
	2006	0.02 (0.01)	0.03 (0.01)	0.08 (0.04)	0.06 (0.02)	0.02 (0.01)
NO_3^-	2004	0.5 (0.1)	0.8 (0.1)	12.4 (3.6)	9.0 (2.7)	3.4 (1.5)
	2005	1.5 (0.3)	2.3 (0.5)	14.9 (6.9)	12.2 (3.4)	5.5 (1.4)
	2006	0.6 (0.2)	1.0 (0.3)	1.8 (0.5)	3.5 (0.9)	1.5 (0.4)
DON	2004	1.1 (0.3)	1.7 (0.4)	14.3 (3.6)	9.7 (2.3)	3.9 (1.1)
	2005	2.8 (0.8)	4.7 (1.7)	7.1 (4.0)	3.6 (1.5)	2.4 (0.7)
	2006	1.0 (0.4)	2.6 (1.7)	2.6 (1.2)	2.6 (1.3)	1.0 (0.4)
TPN	2004	0.1 (0.0)	0.4 (0.1)	0.7 (0.3)	0.5 (0.2)	1.0 (0.5)
	2005	2.2 (1.0)	2.0 (1.1)	3.7 (2.9)	2.5 (1.4)	7.8 (6.1)
	2006	0.4 (0.3)	0.3 (0.1)	0.6 (0.3)	0.4 (0.3)	0.5 (0.2)
TN	2004	1.5 (0.3)	2.6 (0.4)	27.1 (5.2)	18.6 (3.2)	8.2 (3.0)
	2005	6.0 (1.7)	8.3 (3.3)	25.2 (13.7)	17.9 (5.9)	16.0 (7.6)
	2006	1.8 (0.7)	2.3 (0.8)	4.3 (1.4)	5.7 (2.0)	2.8 (0.9)

greater in burned streams during snowmelt and storm-flow events than in reference streams. By 2006, TDN export and TN export during high-flow events in burned streams had declined greatly (Fig. 5) and were not statistically different from those observed in reference streams ($p = 0.37$ for TDN and $p = 0.48$ for TN). NO_3^-–discharge relationships were significantly different between burned and reference streams in 2005 ($p < 0.001$), but not in 2004 ($p = 0.18$) or 2006 ($p = 0.57$).

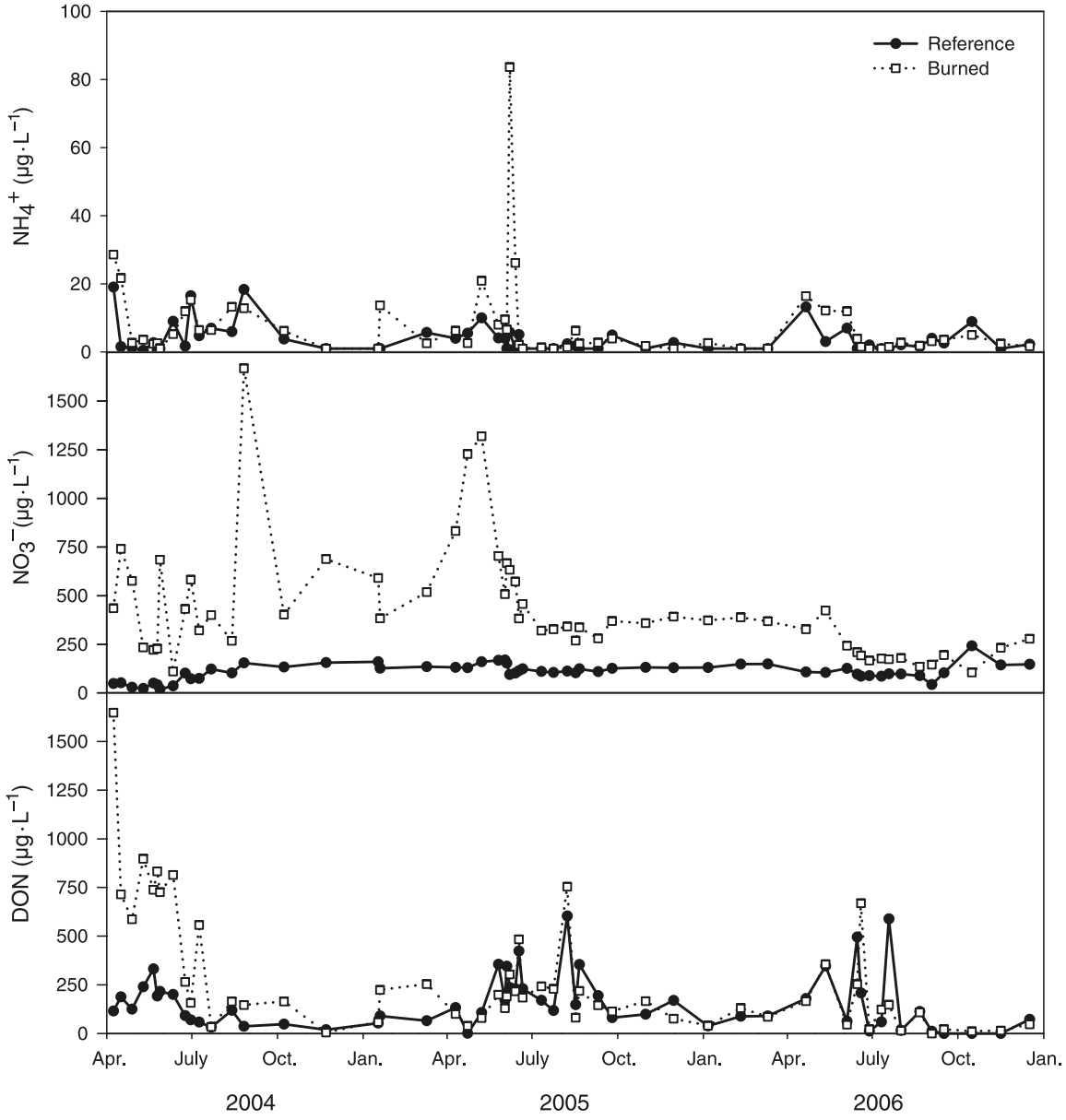
Discussion

The concentrations of nitrate (NO_3^-), dissolved organic nitrogen (DON), total dissolved nitrogen (TDN), and total nitrogen (TN) were 2.0 to 4.9 times greater in streams draining burned watersheds than in reference (unburned) streams in the first 2 years following the Lost Creek wildfire in the Crowsnest Pass (Rocky Mountain region in southwestern Alberta) (Figs. 2 and 3). This resulted in mean nutrient yields that were considerably greater for NO_3^- (7.5-fold), DON (2.7-fold), TDN (4.3-fold), and TN (4.1-fold) in burned streams than in reference streams. Concentrations of NO_3^- and TN were among the highest postfire measurements described in the literature and were much higher than values previously reported for similar regional settings. For instance, following a major wildfire in the headwaters of a watershed in southeastern British Columbia (similar climate, elevation, relief, soils, and vegetation composition as our study), the maximum concentrations observed were 930 $\mu g \cdot L^{-1}$ NO_3^- and 1010 $\mu g \cdot L^{-1}$ TN (Gluns and Toews 1989). In the present study, maximum concentrations for NO_3^- (1667.9 $\mu g \cdot L^{-1}$) and TN (3413.4 $\mu g \cdot L^{-1}$) were 1.7 and 3.4 times greater, respectively, than those reported by Gluns and Toews (1989). Similarly, NO_3^- concentrations ranged from 126 to 427 $\mu g \cdot L^{-1}$ in fire-impacted high-elevation Rocky Mountain watersheds in northwestern Montana (Hauer and Spencer 1998). Moreover, the unburned streams in our study produced a similar range of maximum NO_3^- concentrations (197.1–366.0 $\mu g \cdot L^{-1}$) as the burned watersheds reported by Hauer and Spencer (1998). Dissimilar rates of nitrification between the Lost Creek wildfire region and previous studies could potentially explain some of the differences in stream N (Turner et al. 2007). Further, increased atmospheric N deposition in high-elevation Rocky Mountain ecosystems in recent years (Williams et al. 1996; Campbell et al. 2000; Schindler et al. 2006) may have contributed to the elevated stream-water N concentrations that were observed in both the burned and reference watersheds.

Most studies from other regions also report variable increases in the concentration of various forms of N following wildfire, but typically with lower concentrations than were observed in our study (MacKay and Robinson 1987; Bayley et al. 1992; Gerla and Galloway 1998; Nelson et al. 2007). The strongly elevated concentrations of NO_3^-, DON, TDN, and TN likely reflected the high proportion of watershed area burned and the high fire severity of the 2003 Lost Creek wildfire, where virtually all forest cover and forest floor organic matter were consumed. Additionally, the high precipitation and steep topographic relief (both longitudinal and side valley relief) of the headwater watersheds in this study promote strong hydrologic gradients, driving both surface and subsurface flow paths, likely resulting in stronger coupling of the burned landscape with stream-water quality.

Generally, the random character of wildfire precludes the design of carefully controlled watershed-scale studies. Thus, a critical component of the present analysis is the assumption that the reference sites reflect prefire conditions at the burned sites. Accordingly, it is essential to note that the reference and burned watersheds were similar in slope, aspect, elevation range, soils, and geology; as well, they were similar in forest cover before the wildfire. The elevated postfire N concentrations and specific yields in the burned watershed streams, together with the subsequent and rapid decline in these parameters to levels comparable to those in reference streams, supports the hypothesis that the burn was responsible for the observed differences in N species. If the burned sites naturally produced higher N (i.e., were higher

Fig. 3. Mean daily concentrations for ammonium (NH_4^+), nitrate (NO_3^-), and dissolved organic nitrogen (DON), the various components of total dissolved nitrogen (TDN), in the reference and burned watersheds from 2004 to 2006. Note the different *y*-axis scales.



than reference sites before the burn) then this pattern likely would not have been observed.

Because of the range of N species that were sampled in this study, additional insight into both the likely transport mechanisms and the differential patterns of recovery among N species is possible. The various forms of N may be associated with either surface (erosion of ash from hillslopes; e.g., NH_4^+) or subsurface (dissolved fractions; e.g., NO_3^-) hydrologic flow pathways. TPN and NH_4^+ concentrations and yields across all 3 years were only slightly higher in streams from burned watersheds, while loading was more variable among years than other N forms and was strongly associated with larger discharge events. The correspondence of elevated TPN and NH_4^+ concentrations with larger event flows suggests that near-surface pathways are important mechanisms for transport. For instance, the highest TPN concentration occurred during the large rain-on-snow event in January 2005 (136 mm of precipitation and 25–50 mm of snowmelt over 3 days), during which large amounts of particulate matter (ash), detritus, and sediment (data not shown) were transported to streams in burned watersheds. Similarly, the highest NH_4^+ concentration coincided with a 94.9 mm precipitation event on 6–7 June 2005, which also transported large amounts of sediment to the receiving streams. This observation suggests a high degree of NH_4^+ adsorption to particulate matter. The low NH_4^+ concentration observed throughout most of the study may be additional evidence of high adsorption to cation exchange sites in the soil and is consistent with the strong association of NH_4^+ with larger discharge events. However, it is important to note that low NH_4^+ concentrations could also indicate high rates of nitrification to NO_3^- or plant or microbial immobilization (Turner et al. 2007). Postfire concentrations of NH_4^+ have been observed to be more than 40-fold greater in streams from

Fig. 4. Box-and-whisker plots of ammonium (NH_4^+), nitrate (NO_3^-), dissolved organic nitrogen (DON), total particulate nitrogen (TPN), and total nitrogen (TN) concentration from 2004 to 2006 separated by base flow, snowmelt freshet, and storm flow for the reference and burned watersheds. Note the different *y*-axis scale for NH_4^+.

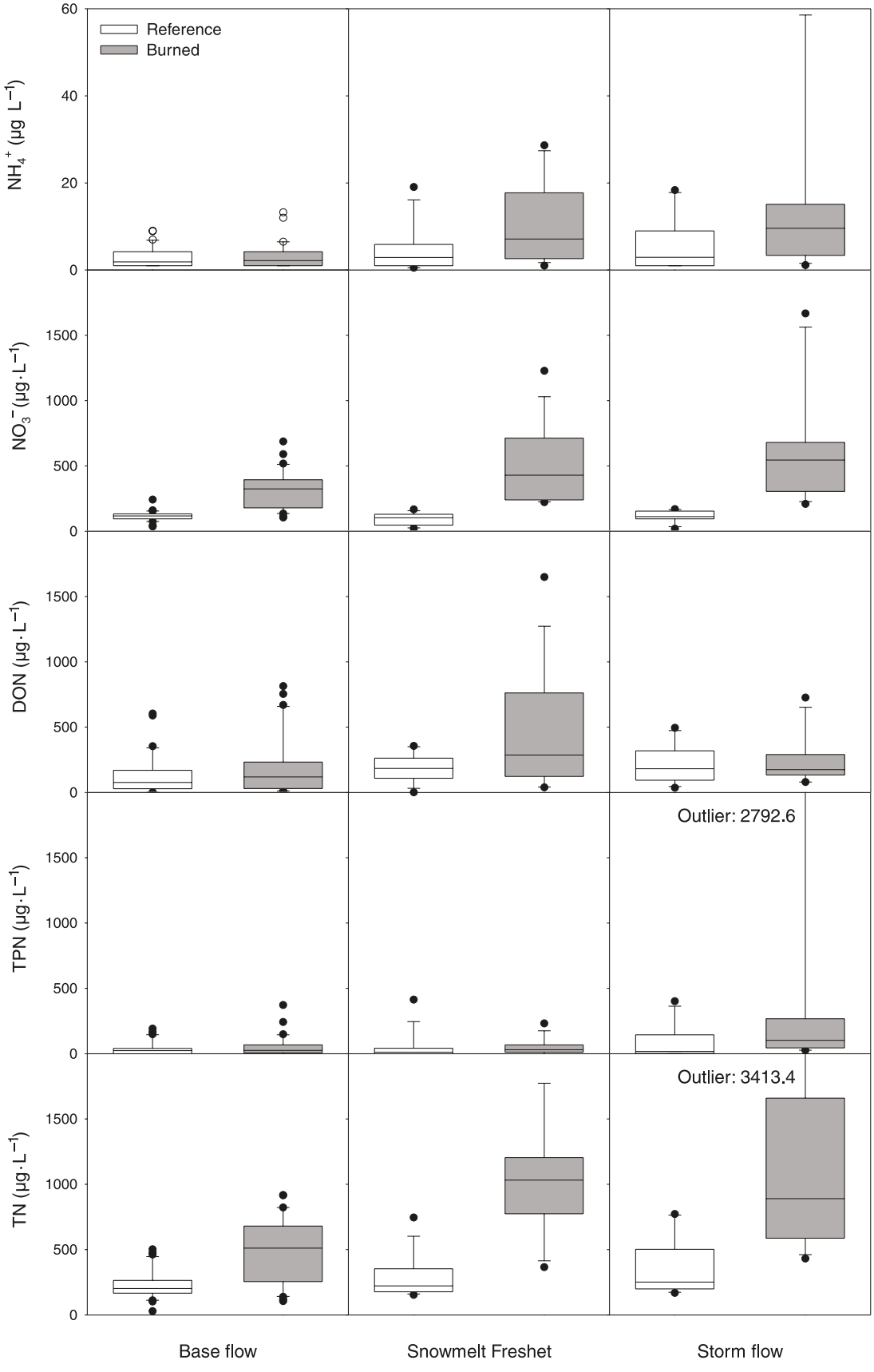
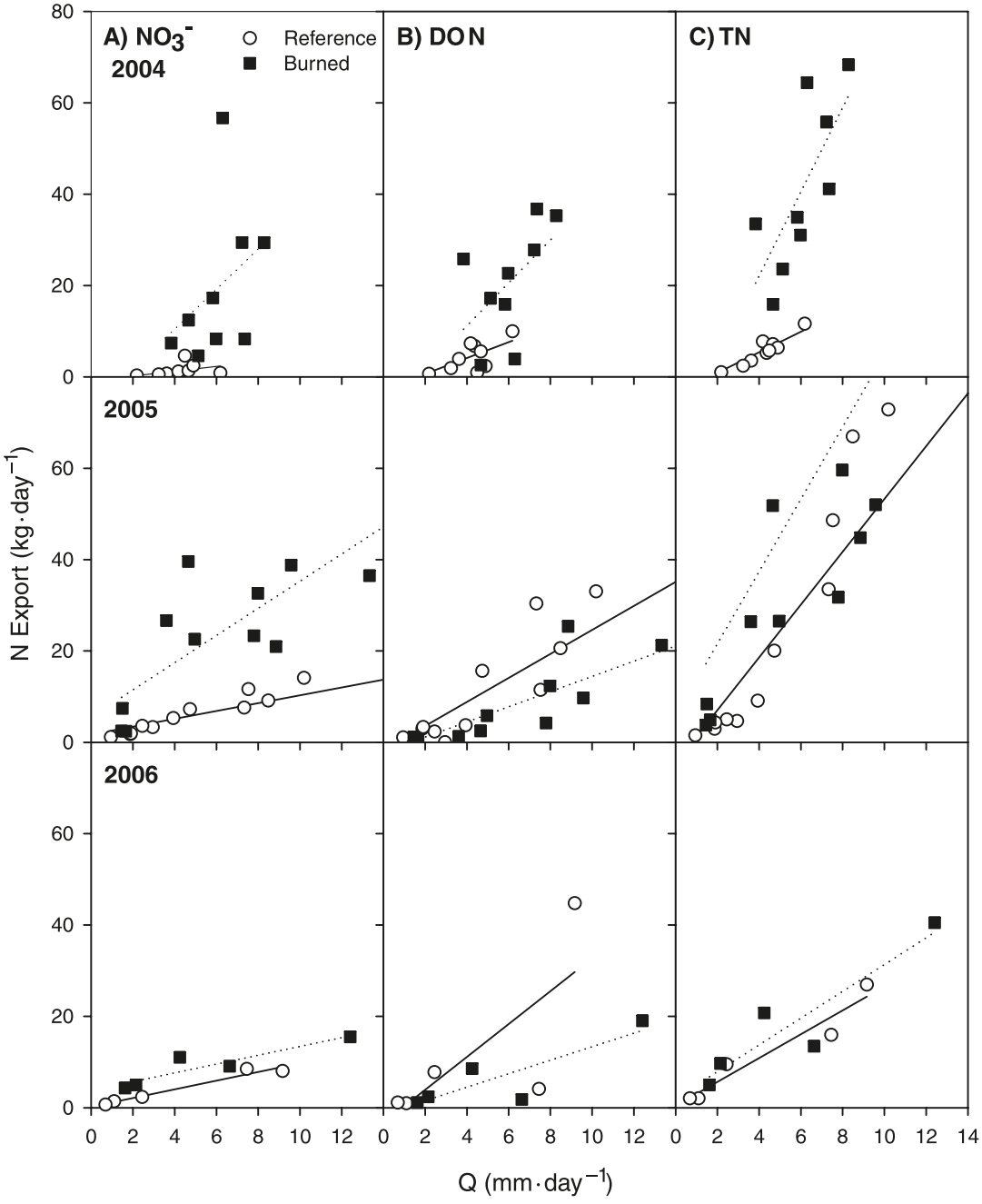


Fig. 5. Relationship between streamflow (Q) and (A) nitrate (NO_3^-), (B) dissolved organic nitrogen (DON), and (C) total nitrogen (TN) export in the reference and burned watersheds during the snowmelt freshet and storm-flow events for 2004, 2005, and 2006.



burned watersheds than from the control streams; however, these levels were also shown to decline to background levels only a few months after the fire (Spencer and Hauer 1991). Thus, it is also possible that a large increase in stream-water NH_4^+ occurred immediately after the fire in the fall of 2003 (2 months before freeze-up), but was not observed because stream sampling started during the subsequent snowmelt period (early spring 2004).

Temporally, the trends for TDN and TN differed from that evident for TPN (Fig. 2). Though most of the events producing the greatest TDN and TN concentrations in burned streams occurred in 2004, the concentrations generally remained elevated throughout 2004 and 2005, including during base-flow conditions. Additional analyses of the components of TDN showed strong differences in the temporal trend of NH_4^+, NO_3^-, and DON (Fig. 3). Concentrations of DON during the first postfire spring were very high (maximum: 1649.1 $\mu g \cdot L^{-1}$), likely because of the rapid leaching of some forms of DON, which is highly mobile but resistant to breaking down into mineral N forms (Neff et al. 2003). These characteristics of DON are likely responsible for our observation that DON production recovered more rapidly than other N forms (Fig. 5). DON has been well correlated with dissolved organic matter, which also had high concentrations in the first postfire year (data not shown), likely as a result of hydrophobic soils, reduced infil-

tration rates, and increased runoff (Wondzell and King 2003).

Other available N forms, particularly NO_3^-, would have been released rapidly through initial thermal decomposition (pyrolysis) of organic matter by fire (Smithwick et al. 2005), followed by increased mineralization of any remaining organic N (i.e., partially burned plant material) and increased rates of nitrification and mobilization (Tiedemann et al. 1978; Ranalli 2004). Though lower than in the first two postfire seasons, wildfire effects were still evident in the third year, with elevated NO_3^-, TDN, and TN exports and concentrations in burned watersheds during the spring freshet and storm-flow events. While this trend for N export and concentration for the 3 years after the wildfire was generally consistent with results of previous studies, the decline was among the more rapid of those previously reported (Gluns and Toews 1989; Bayley et al. 1992; Minshall et al. 1997; Hauer and Spencer 1998). The comparatively short duration of the increase in stream-water N in our study is most likely related to the high intensity and severity of the Lost Creek wildfire (i.e., reduced organic matter available for nitrification), the steep slopes and hydraulic gradients of the burned watersheds, and the very high precipitation across the study region (i.e., rapid mobilization of available N). The high precipitation combined with the steep hydrologic gradient imposed by the relief can produce substantial subsurface or groundwater flow in these headwater regions (Rock and Mayer 2007). This may have rapidly transported the soluble forms of N into the receiving streams, leading to a shorter duration of elevated stream-water N. As revegetation has been slow because of the severity of the burn in these high-elevation watersheds, immobilization due to vegetation uptake is likely to have had a smaller influence on initial (3 year) N recovery in this study. While several physical and biogeochemical factors may have influenced the concentrations of NO_3^-, as well as that of the other N forms, in streams draining burned watersheds, the rates and magnitudes of these processes were not quantified in the present study and warrant further investigation to more fully elucidate the contributing factors.

The highest concentrations of NO_3^-, TDN, and TN generally coincided with the highest discharge, which occurred during the spring freshet and following precipitation events (Fig. 4). Because virtually all forest cover and forest floor organic matter were consumed by the fire, the precipitation interception capacity was greatly reduced in the burned watersheds. Thus, during snowmelt or precipitation events the burned areas likely contributed greater surface and subsurface water to streams than did unburned areas, thereby greatly increasing the transport of nutrients to the burned streams. Many of the highest concentrations in these dissolved N species (particularly NO_3^- and TN) occurred early in the snowmelt period (rising limb of the annual hydrograph) when percolation of melt water from ripe snowpacks to the ground surface would be at its peak. Our observations are similar to those of others who have observed large pulses or peak NO_3^- and TN concentrations during the snowmelt freshet or after storm-flow events (Gluns and Toews 1989; Brass et al. 1996; Hauer and Spencer 1998). These events also produced much greater variability in the different N species concentrations (Fig. 4), as a result of variation in event size and antecedent moisture storage conditions. While there were large differences in N concentrations between burned and reference watersheds during snowmelt and storm flow, small differences in concentrations of the various N species were still evident during base-flow periods, highlighting the importance of groundwater and subsurface contributions to the headwater streams in this study. The differences observed suggest limited N immobilization and effective leaching to groundwater in the burned watersheds (Chorover et al. 1994).

Conclusions

The objectives of this study were to quantify the initial magnitude of postfire changes in various nitrogen (N) species and to describe the temporal trend of early N recovery in streams following a severe wildfire in several high-water-yielding Rocky Mountain headwater watersheds in southern Alberta. As expected, the concentrations, exports, and yields of many N species (NH_4^+, NO_3^-, TDN, and TN) were significantly higher in the burned streams in the first postfire year than in the reference streams.

The temporal trend of recovery of the various N forms towards levels similar to those of the reference watersheds was heterogeneous and most likely due to variability in N form mobility. Three years after the fire, elevated NO_3^-, TDN, and TN concentrations, yields, and exports were still evident during the snowmelt freshet and following precipitation events. The effects of the burn were most noticeable (i.e., produced the greatest N concentrations, yields, and exports) during or following higher discharge periods (snowmelt freshet and storm flows).

Given the predictions for increased wildfire season length, as well as wildfire frequency and severity, a clear understanding of the potential impacts on water quality is likely to become increasingly important. However, knowledge in this area is incomplete because of a shortage of studies assessing the initial effects and recovery from this natural disturbance, especially in headwater systems. While this study contributes to our understanding of wildfire impacts on water quality, additional research on postdisturbance processes is needed, especially in regions that are predicted to be most greatly impacted by climate change

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