The effects of wildfire on sediment-associated phosphorus forms in the Crowsnest River basin, Alberta, Canada

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Abstract The impacts of large-scale land disturbance by wildfire on a wide range of water and related ecological services are increasingly being recognized worldwide. This study explores the long-term impact (6–7 years) of the 2003 Lost Creek wildfire on particulate phosphorus forms (NAIP, AP, OP) of suspended river sediment at a large regional scale (554 km^2) in the Crowsnest River basin, Alberta, Canada. While total P concentrations were similar among burned and unburned river sediments, the mean bioavailable NAIP fraction remained approximately 70% greater and the organic P over 2-fold higher in sediments from five burned tributary watersheds compared to the reference site in the Crowsnest River study catchment. Because of the key role of phosphorus in regulating aquatic productivity in oligotrophic mountain rivers, these findings highlight the risk of a large scale and long-term legacy of wildfire in some mountain river systems.

Key words wildfire; phosphorus speciation; bioavailability; propagation

INTRODUCTION

Phosphorus (P) enrichment of surface waters has resulted in the eutrophication of many freshwater environments (Wall *et al*., 1982; Cooke *et al*., 1986). This global water quality problem has had significant impacts on aquatic ecology (Carpenter *et al*., 1998; Correll, 1998) and the cost of water treatment and supply (Emelko *et al*., 2010). Elevated P levels in rivers can increase the growth of periphyton and epiphytic diatoms, which often accelerate biofilm growth (House, 2003). The incidence and severity of this environmental problem varies spatially and temporally, and is governed by a number of factors that control the source, redistribution and bioavailability of P (Withers & Jarvie, 2008). Diffuse agricultural and urban sources represent the predominant inputs of dissolved and particulate P (PP) loading to receiving freshwaters (Dillon & Kirchner, 1978; Hill, 1981; Bird, 1986; O'Driscoll *et al*., 2010). Other factors such as precipitation (Macrae *et al*., 2010) and geology (Grobler & Silberbauer, 1981) influence the source, delivery pathways (surface and subsurface), composition (concentration, speciation and bioavailability) and fate of P in aquatic systems (Withers & Jarvie, 2008).

Phosphorus production in most undisturbed forested landscapes is usually low (Burke *et al*., 2005); however, disturbance of forests by wildfire can dramatically increase sediment erosion rates and sediment-associated nutrient fluxes from fire-affected forests. Smith *et al*. (2011) report that wildfire can increase P production in streams from 0.3 to over 5 times greater than unburned conditions. Furthermore, plot scale studies suggest the relative bioavailability of P may increase in burned soils (Blake *et al*., 2009, 2010). While sediment is the primary vector for the delivery of P to receiving freshwaters along with subsequent transport and storage and remobilisation within streams and rivers, comparatively few studies have explored post-fire P dynamics at larger basin scales. Given growing concern about the potential downstream effects of wildfire on water quality in many regions, there is a need to study these coupled sediment–nutrient dynamics in larger wildfire-affected river systems. The source waters at risk of wildfire represent essential water supplies for many cities and their protection from enhanced nutrient inputs is therefore desirable.

Sequential extraction techniques have been widely used to determine phosphorus (P) forms in aquatic sediments (Logan *et al*., 1979; Ostrofsky 1987; Nürnberg 1988; Stone & English, 1993; Stone, 2004; Pacini & Gachter, 2008) and to estimate the release potential of P to the water column (Rydin, 2000; Reitzel *et al*., 2005). Particulate P fractions are "operationally" defined by the extracting agent and the extraction conditions used (Psenner *et al*., 1988). Sequential extraction techniques have been used to evaluate spatial and temporal variation in PP forms in rivers draining urban and agricultural landscapes (Logan *et al*., 1979; Stone & English, 1993; Pacini & Gachter, 1999). However, no studies have been conducted specifically to evaluate PP forms in rivers draining landscapes disturbed by wildfire. Given the global increase in wildfire (Westerling *et al*., 2006) and its potential impacts on water supply and treatment (Emelko *et al*., 2010), there is a need to characterize sediment-associated P forms in streams disturbed by wildfire in order to assess their bioavailability and potential impact on downstream water quality. Accordingly, the objective of this study is to quantify the effects of wildfire on the PP forms (NAIP, AP, OP) of suspended river sediment at a larger, regional basin scale (554 km^2) in southern Alberta, Canada. Some implications of the study for downstream water quality and its management are discussed.

METHODS

Study area

The study was conducted in the Crowsnest River basin in southwestern Alberta, Canada (Fig. 1). Elevations in the region range from 1100 to 3100 m and vegetation consists primarily of mixed conifer forests at lower elevations and subalpine forests at mid elevations. At higher elevations, alpine ecozones are characterized by alpine meadow vegetation and bare rock extending above the tree line. Annual precipitation varies from 700 to 1700 mm, approx. 55% of which falls as rain during the frost free period. The mean annual (2000–2009) river discharge in the Crowsnest River (gauged at Frank, AB between tributaries 3 and 4; Fig. 1) was 341 mm and the annual hydrograph reflects a strong snowmelt-dominated seasonal response along with significant groundwater contributions to baseflows (Rock & Mayer, 2006).

In 2003, the Lost Creek Fire generated a near contiguous crown fire that consumed nearly all forest cover over 21 000 ha in the headwater regions of the Castle and Crowsnest rivers. Unpublished data for 2004–2011 indicates that the concentration, export and yields of both sediment and P in the burned watersheds have yet to recover to pre-burn conditions, thus illustrating the severity and prolonged impact of this mass landscape disturbance on sediment and P fluxes. The Lost Creek wildfire occurred immediately upstream of the Oldman Dam (Fig. 1) and there is concern regarding the water quality implications of enhanced sediment and P fluxes to the reservoir from burned landscapes.

Sample collection

Composite samples of suspended solids were collected passively with a network of *in situ* time-integrating samplers (Phillips *et al*., 2000). These samplers provide a simple and pragmatic means of sampling the natural variation in sediment properties during snowmelt and storm events in rivers (Phillips *et al*., 2000) and are routinely used to collect a sufficiently large sample mass for laboratory analyses in studies designed to evaluate the geochemical and contaminant properties of fluvial sediment (e.g. Walling *et al*., 2008).

Time-integrating samplers were deployed in the Crowsnest River at locations upstream and downstream of the wildfire and in five wildfire impacted streams tributary to the Crowsnest River (Fig. 1). The upstream sample location on the Crowsnest River (site 1) represents a relatively undisturbed (reference) sub-catchment. The tributary sampling locations (sites 2, 3, 4, 5, 6) drain catchments impacted to varying degrees (8 to 100%) by wildfire (Table 1). The downstream Crowsnest River location (site 7) was selected to examine the combined signatures of sediment P fluxes from the burned catchments on the sediment quality of the Crowsnest River at a large (554 km^2) basin scale. Time-integrating samplers were installed each spring prior to snowmelt and composite sediment samples were collected three times in 2009 and twice in 2010. Sediment samples were frozen for storage prior to chemical analysis.

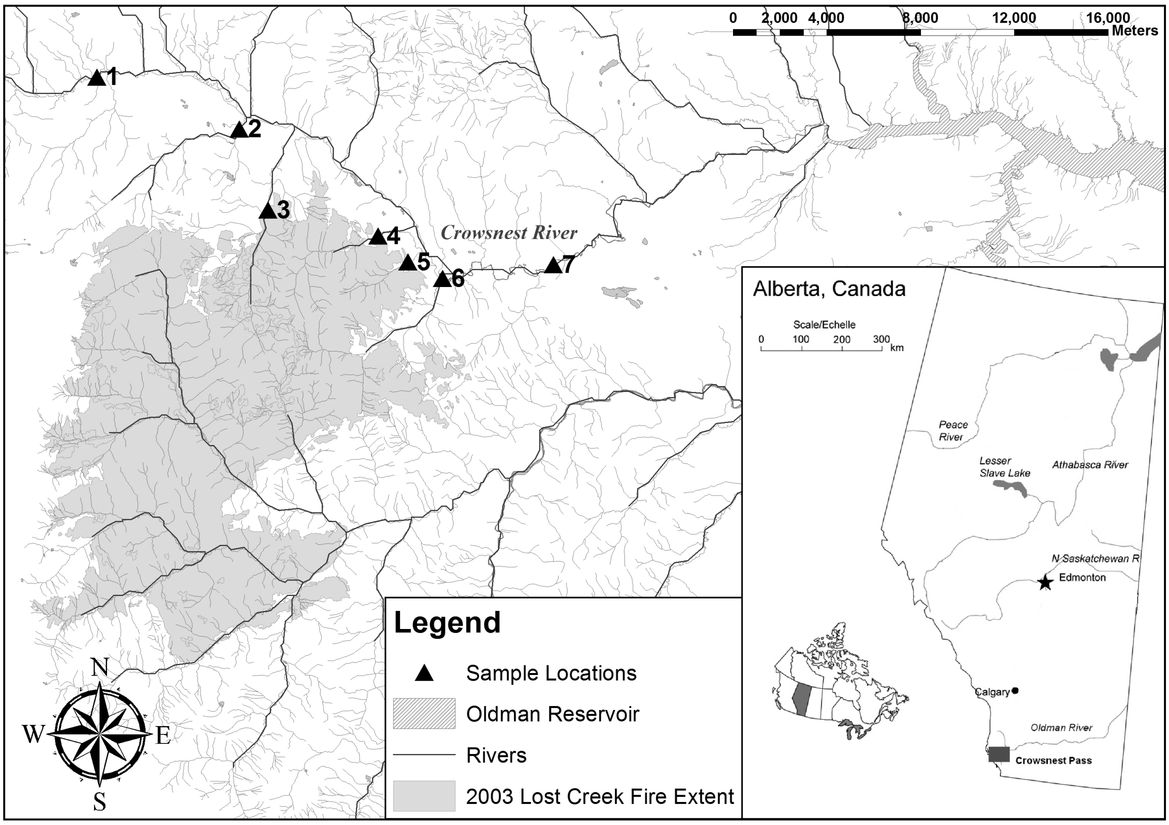

Fig 1 The study area and river suspended sediment sampling locations.

Table 1 Characteristics of the study sub-catchments.

Site	River	Upstream drainage area (ha)	Upstream burn Area (ha)	% Upstream burned	% Upstream salvaged logged
Reference					
1	Crowsnest River	16 076	0	0	-
Burned tributaries					
2	York Creek	3 365	271	8	-
3	Lyons Creek	2 650	1 703	64	21
4	Drum Creek	1 179	1 064	90	-
5	Unnamed Creek	478	450	94	-
6	Byron Creek	2 511	1 508	60	5
Downstream mainstem					
7	Crowsnest River	55 387	5 300	10	1

Particulate P fractionation

A sequential extraction scheme was used to quantify the relative fractional composition of PP forms in sediment samples. The fractionation scheme yields five operationally-defined fractions of PP (Stone & English, 1993). In order of extraction, these PP fractions are: (a) loosely sorbed P; (b) reductant soluble P; (c) reactive P sorbed to metal oxides; (d) P bound to carbonates, apatite P and P released by the dissolution of oxides; and (e) non-reactive organic P extractable in hot (85°C) NaOH. The first three fractions combined are considered to be bioavailable and referred to collectively as non-apatite inorganic P (NAIP). Fractions four and five are referred to as apatite P

(AP) and organic P (OP), respectively. The OP fraction is potentially available after mineralization (Bostrom *et al*., 1988). After centrifugation, extracts were analysed on a Technicon Autoanalyzer using the stannous chloride ammonium molybdate method (Environment Canada, 1979). The detection limit of the analytical method is 1 μg/L.

RESULTS AND DISCUSSION

Phosphorus speciation

Due to the importance of sediment-associated transport for the flux of nutrients within river basins, a number of studies have been conducted to characterize the PP forms in both suspended and deposited sediment in rivers and lakes. Owens & Walling (2002) reported that the phosphorus content of fluvial sediment in rural and industrialized river basins typically ranges between 100 and 13 500 μg/g. In a variety of calcareous and non-calcareous lakes, total PP concentrations were reported to range from 580 to 7000 μg/g (Williams *et al*., 1976; Peterson *et al*., 1988; Ostrofsky & McGee, 1991; White & Stone, 1996). In the present study, the total PP content ranged from 543 to 787 μg/g (Fig. 2), which is much lower than the PP levels commonly measured in rivers and lakes directly impacted by urban and agricultural land use. However, the undisturbed headwater streams on the eastern slopes of the Rocky Mountains are typically oligotrophic and increased TP concentrations due to wildfire in the study area have dramatically increased stream productivity and biofilm growth (Silins *et al*., 2009). The increased biofilm growth has decreased the erodibility of cohesive sediment deposits in wildfire affected streams (Stone *et al*., 2010).

Longitudinally, the average concentration of the NAIP fraction in the Crowsnest River increased from 163 μg/g at the upstream (site 1) to 386 μg/g at the downstream sampling location (site 7; Fig. 2). As a percentage of total P, NAIP increased by a factor of 2 from 26% to 52.5% (Table 2). The NAIP fraction in the burned tributary sediments (sites 4, 5, 6) and the most downstream location on the Crowsnest River (site 7) was greater than the upstream reference site. With the exception of Lyons Creek, the NAIP content increased with the spatial extent of burn in the corresponding sub-catchment. Accordingly, the highest average NAIP fraction concentration was observed in Drum Creek, which experienced a 90% burn during the 2003 wildfire.

The bioavailability of sediment-associated P for plant uptake depends upon several interrelated physical, chemical and biological factors (Bird, 1986). Grain size is one factor that strongly influences the major element composition and distribution of PP forms in aquatic sediment (Stone & Mudroch, 1989; Stone & English, 1993). The median diameter (D_{50}) of suspended solids collected from the reference, burned and downstream Crowsnest River sample stations ranged from 16 to 59 μm. The NAIP fraction associated with these fine-grained materials indicated that the potential bioavailability of sediment-associated P in the tributary sediment from the burned catchments is 1.2 to 2.6 times higher than the upstream reference site on the Crowsnest River.

The average AP content in sediment was much greater in the upstream reference site than at either the burned tributaries or most downstream site on the Crowsnest River (Fig. 2). The respective AP fraction of PP decreased from 61% at the reference site to 38% at the downstream Crowsnest River site. A dilution of the AP signal at site 7 is related to lower AP content from tributary inputs, particularly Drum Creek, which has high sediment yields but a low AP fraction (26% of total P). DePinto *et al.* (1981) measured algal-available phosphorus in suspended sediments collected from the Maumee, Sandusky and Cattaraugus rivers. They observed that total P content varied by less than 5% from levels that were reported in an earlier investigation of the same rivers. Accordingly, the authors suggested that PP content may be a temporally stable characteristic for any given tributary. Similarly, Stone & English (1993) observed low seasonal variability in the AP fractions in sediment collected from two southern Ontario rivers. Their observation supports the contention of Thomas & Munawar (1985) that AP is a constant background form of P in the tributaries of the lower Great Lakes. Burrus *et al*. (1990) examined the seasonal delivery of PP forms to Lake Geneva from the upper Rhone River and found that AP content remained constant throughout the year. In the present study, the AP content was measured

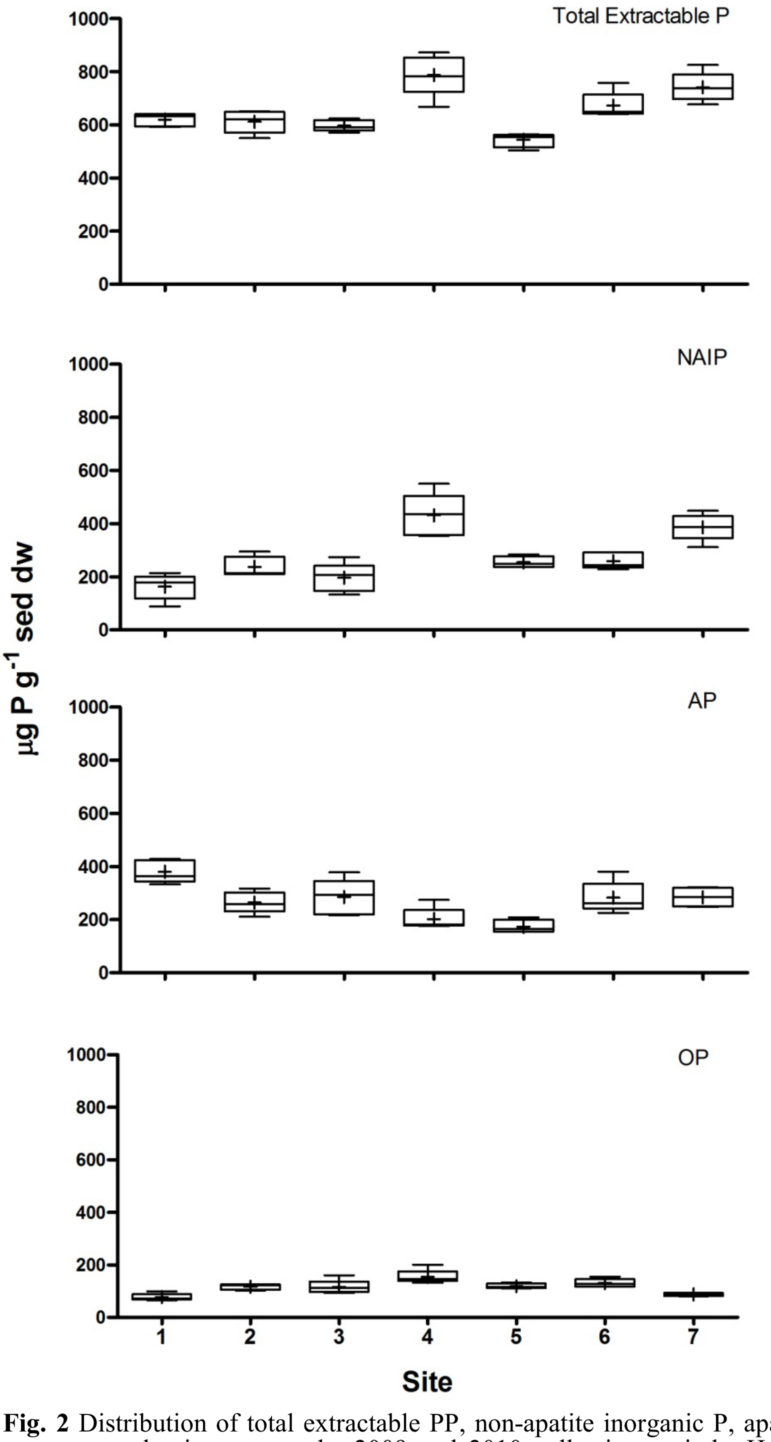

Fig. 2 Distribution of total extractable PP, non-apatite inorganic P, apatite inorganic P, and organic P among sample sites across the 2009 and 2010 collection periods. Horizontal line indicates median, boxes indicate 25th and 75th percentiles, whiskers indicate range, and + indicates the mean.

seven times over a two year period, but varied by <0.5%. The high AP concentration observed at site 1 indicates there is a strong geological control on the PP fractionation in the catchment above the reference sediment sampling site. Given the low variability of AP at site 1, it can be expected that any variation in total PP export will likely reflect variation in the NAIP and OP fractions resulting from land use disturbance in the Crowsnest River such as wildfire and salvage logging.

Table 2 NAIP, AP and OP as a percentage of total PP for the study sites.

Site	*n*	% NAIP of TP	% AP of TP	% OP of TP	TP
Reference					
1	7	26.3	61.3	12.5	619.2
Burned tributaries					
2	7	38.8	43.2	19	611.5
3	6	32.9	47.7	19.4	596.3
4	5	54.8	25.7	19.6	787
5	6	46.8	31.8	21.8	543.6
6	6	38.5	42.1	19.4	671.7
Downstream mainstem					
7	9	52.1	38.4	11.9	741.2

The average OP fraction in the Crowsnest River increased slightly from site 1 (77 μg/g) to (88 μg/g) at site 7 (Fig. 2). However, there was a 1.5- to 2-fold increase in the OP fraction of the tributary sediment compared to the upstream reference site. Compared to streams draining unburned landscapes, the impacted tributaries have experienced accelerated and sustained algal/biofilm growth since the Lost Creek wildfire in 2003 (Silins *et al*., 2009). The higher OP particulate fraction observed in the burned tributaries likely includes organic materials eroded and remobilized from the stream bed during higher flow events.

While the impact of wildfire on nutrient production has received increasing research attention over the past decade, the issue of potential impacts on larger river systems downstream of wildfires remains uncertain. Hauer & Spencer (1998), Burke *et al.* (2005), and Mast & Clow (2008) all reported significant impacts of wildfires on larger river systems (106–248 km^2) that were detectable up to 4 years after wildfire. In the present study, while the 2003 Lost Creek wildfire burned a large region of the headwater between the Crowsnest and Castle river basins, the fire affected region of the Crowsnest River at site 7 only comprised 10% of a 554 km^2 basin. Moreover, the signature of this wildfire on increased bioavailable P forms was clearly evident in suspended river sediments 6 and 7 years after the wildfire of 2003. The foregoing supports the idea that sediment-associated contaminant storage and transport downstream of wildfire affected regions is an important component governing the spatial scale and longevity of potential downstream effects of wildfires that will need increased attention to understand better the range of impacts of wildfires on lotic ecosystems. The observed legacy of elevated sediment and associated NAIP delivery from burned landscapes to the Crowsnest River and downstream aquatic environments will have implications on water quality in the Oldman Reservoir. The eastern slopes of the Rocky Mountains are critical source water regions in Alberta. The potential impact of wildfire on a range of ecosystem services and long-term water supply to municipalities, associated with increased sediment-associated nutrient pressures, is a potential concern requiring well-integrated landscape-level planning and management programmes.

CONCLUSIONS

The results of this study clearly showed a longitudinal increase in the bioavailable NAIP fraction of suspended solids downstream of a burned region of the Crowsnest River basin, relative to a reference site upstream of the 2003 Lost Creek wildfire. The storage and transport of NAIP-rich sediments is likely implicated in the longevity of the effects we observed 6–7 years after the 2003 wildfire and, in turn, these processes may have important implications for water quality in the Oldman Reservoir further downstream. The longer-term propagation of landscape disturbance impacts resulting from wildfire requires further research to continue reinforcing findings such as those reported here.

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