Sediment yields and water quality effects of severe wildfires in southern British Columbia

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Abstract Following wildfire, significant erosion and water quality impacts can occur. However, in British Columbia (BC), Canada, such impacts have seldom been reported. In 2007, several large wildfires occurred in southeastern BC, some in community watersheds. Research sites were established at three fire locations, and plot-scale measurements were made of erosion using silt-fence sediment traps. Watershed-scale measurements of runoff, sediment yield and chemical water quality were made on the Sitkum fire, which burned 39% of a community watershed. A nearby research watershed provided a comparison. Significant surface erosion occurred in some burned areas, but watershed-scale sediment yield increased only slightly, as little sediment reached stream channels. Nitrate levels were elevated after the fire, but were well within accepted limits for drinking water quality. The minimal effects on physical water quality are probably due to low rainfall intensities, the nival runoff regime, and low connectivity between slopes and stream channels in a glaciated landscape.

Key words post-wildfire erosion; wildfire; sediment yield; turbidity; water quality; nitrate; British Columbia, Canada

INTRODUCTION

The incidence of large, severe wildfires in southern British Columbia (BC), Canada, has apparently been increasing in the last several decades, most dramatically with the extreme fire season of 2003 (Filmon *et al*., 2004). After the 2003 fires, floods and landslides caused severe damage to property, infrastructure, and stream channels below five fires (Jordan & Covert, 2009). Such events had rarely or never been documented previously in Canada, although similar post-wildfire events have often been observed elsewhere (e.g. Shakesby & Doerr, 2006). In 2007, 2009, and 2010, severe wildfire seasons again occurred in parts of southern BC, with many fires burning near populated areas, including watersheds used for community and domestic water supply.

Although there is often concern that drinking water quality will be adversely affected by wildfires, there have been few reports of significant impacts on water quality in BC, other than minor increases in turbidity in the first year after the fires. The exception to this general observation is the few stream channels in which large debris flows or debris floods have occurred (Jordan & Covert, 2009).

In 2007, the BC Forest Service began a research project to investigate post-wildfire natural hazards. Several large wildfires occurred in 2007 near populated areas in southeastern BC, which provided opportunities to study the effects of fires on the hazards of landslides, erosion and flooding. The project included measurements of soil erosion at study plots on four fires, and watershed-scale measurements of streamflow, sediment yield and water quality sampling on one fire. In this paper, the results of these measurements are discussed in the context of drinking water quality.

PHYSICAL WATER QUALITY IMPACTS OF WILDFIRE

The most frequently reported effect of wildfire on water quality is increased sediment concentration. In many studies from the USA, substantial increases in soil erosion, turbidity, and suspended sediment concentration following wildfires have been documented (Beschta, 1990; Robichaud *et al.*, 2000; Neary *et al.*, 2005; Moody & Martin, 2009). In most cases, the source of sediment is soil erosion in burned areas, the amount of which depends on soil burn severity, the degree of water repellency and the rainfall intensities that occur after burning (Robichaud *et al.*, 2000; Doerr *et al.*, 2006). An increase in peak streamflow after a fire can entrain additional sediment from erosion of channel banks, and an increased incidence of debris flows in susceptible terrain can also cause high suspended sediment concentrations downstream (Beschta, 1990).

In western Canada, three studies have examined the effects of large wildfires on the water quality of streams. The first, reported by Gluns & Toews (1989), sampled water quality for three years following a wildfire in Matthew Creek in southeastern BC, a community watershed supplying drinking water to the city of Kimberley. The fire burned the lower portions of two tributaries of Matthew Creek, and samples were collected at points upstream and downstream of the burn on these two streams and at corresponding locations on an adjacent unburned tributary. Gluns & Toews (1989) did not observe any significant increase in turbidity, although they noted that their sampling schedule (biweekly during the spring freshet period) was unsuitable for detecting changes in turbidity or suspended sediment responses, which are transient in nature and characterized by high temporal variability. Secondly, a study of water quality after a large wildfire in the Crowsnest Pass area of southwestern Alberta (Bladon *et al*., 2008; Silins *et al*., 2009) collected samples in seven watersheds of similar size, including five which were entirely or partly burned, and two unburned reference watersheds adjacent to the fire. They collected daily samples using automatic pump samplers, and observed suspended sediment concentrations ranging from 6 to 15 times greater in the burned, compared to the unburned watersheds. Thirdly, following the 2003 McClure fire near Barriere, BC, Eaton *et al.* (2010) monitored streamflow and suspended sediment concentration for four years in Fishtrap Creek, a watershed which was 62% burned, and a nearby similar but unburned watershed. They did not observe any difference in suspended sediment response.

CHEMICAL WATER QUALITY IMPACTS OF WILDFIRE

Following wildfire, concentrations of some solutes in streamwater can increase as a result of several processes, including loss of vegetation and the resulting reduced uptake of nutrients from the soil, leaching of solutes from ash and increased erosion of the burned soil by surface runoff (Beschta, 1990; Neary *et al.*, 2005). Numerous studies have shown that increased nutrient concentrations in water can follow forest disturbances including harvesting, prescribed burning and wildfire, with the effects generally increasing in that order (Neary *et al.*, 2005; Pike *et al.*, 2010). Higher burn severity is likely to lead to greater water quality effects, due to greater consumption of organic material and corresponding increased soil erodibility (Pike *et al.*, 2010).

Nitrogen is the nutrient which usually shows the greatest increase after fire. Nitrate (NO_3) is the form of nitrogen of most interest, as it is more mobile and typically occurs in much greater concentrations than NO_2, NH_4 and dissolved organic nitrogen (Neary *et al.*, 2005; Bladon *et al.*, 2008). Substantial increases in NO_3 concentrations have often been observed following wildfire, but these have rarely exceeded drinking water quality guidelines (Neary *et al.*, 2005; Smith *et al.*, 2011). Other solutes that have been found to increase in some studies include PO_4, SO_4 and organic carbon (Neary *et al.*, 2005; Pike *et al.*, 2010).

At Matthew Creek, Gluns & Toews (1989) measured a large increase in NO_3 concentration in the burned watersheds, which was greatest in the second year after the fire. Lesser, but significant, increases in other parameters were observed, including PO_4, total alkalinity and total hardness. Following the Crowsnest Pass wildfire, Bladon *et al.* (2008) reported increases in the concentration of various forms of nitrogen in burned areas, ranging from 1.5 to 6.5 times those observed in the unburned watersheds. The increase was greatest in the first year after the fire, and declined for the following three years. A similar increase occurred for phosphorus (Silins *et al.*, 2009), with the greatest increase observed in the second year after the fire. In neither of these studies, however, was the drinking water quality guideline for nitrate (10 mg/L NO_3 as N; BC Ministry of Environment, 2009) exceeded. There is no published drinking water guideline for phosphorus in either BC or Alberta, but a suggested federal-provincial guideline is 0.2 mg/L (Gluns & Toews, 1989) and this was not exceeded in either study following the respective wildfires.

STUDY SITES AND METHODS

Following the 2007 wildfires in southeastern BC, study sites were located in the burned area of three fires: the Sitkum fire near Nelson; the Springer fire near Slocan; and the Pend d'Oreille fire near Trail (Fig. 1). In 2009, a study site was added in the area burned by the Terrace Mountain fire near Kelowna, with the objective of including a lower elevation, drier, forest type. The respective areas burned by these fires were approximately 3100, 1100, 4000 and 9300 ha, and they included a substantial proportion of high burn severity. The study sites covered only a small portion of each fire; they were chosen on the basis of access, high burn severity and areas which presented high risks to downslope or downstream values, such as public safety or community water supplies. Some summary information for each study site is given in Table 1.

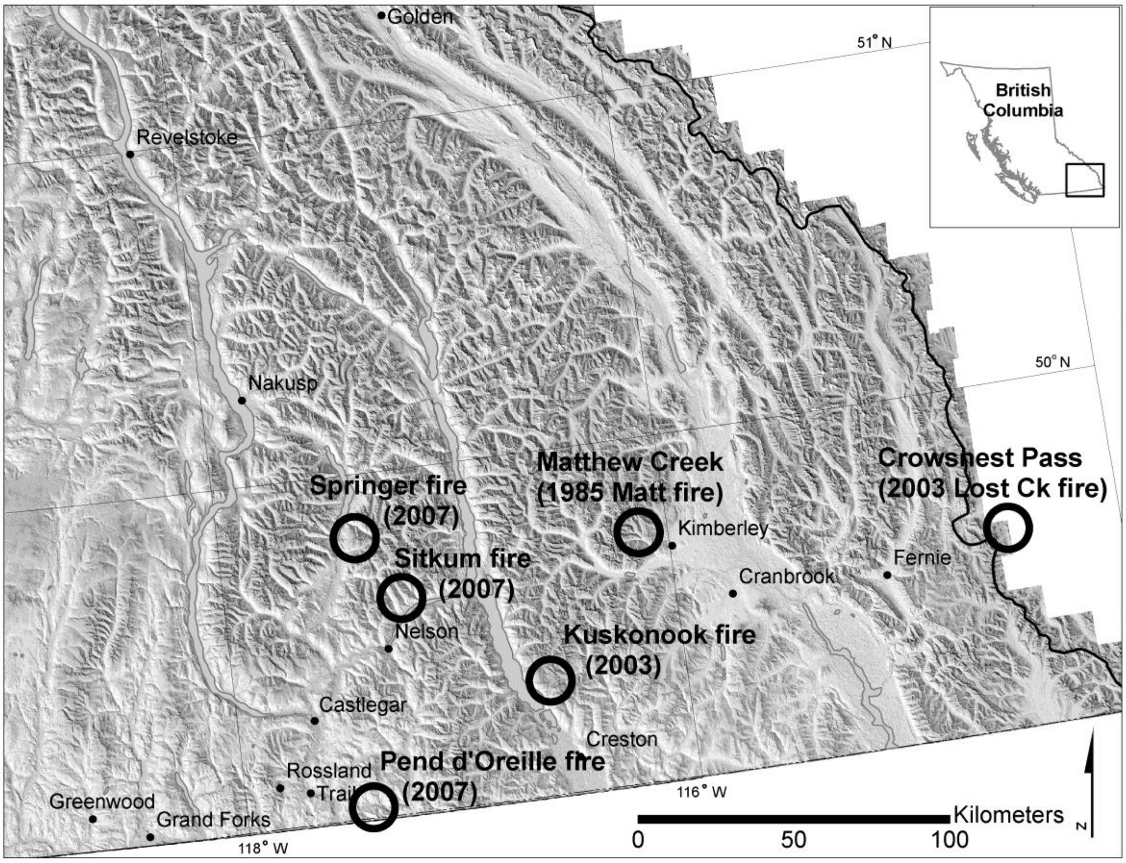

Fig. 1 Location map of southeastern British Columbia, showing the wildfires referred to in this paper. (The Terrace Mountain fire is to the west of this map.)

Table 1 Site characteristics and data from the soil erosion plots for each year after each fire.

Fire and year[1]	Elevation	Aspect	Soil texture[2]	Precipit-ation (mm)[3]	Mean sediment yield from erosion plots (Mg/ha); years after fire				
					n[4]	0	1	2	3
Springer (2007)	1465–1560	SW	SL	970	6	0.44	4.15	0.69	0.22
Sitkum (2007)	1600–1800	NE	SL	1290	2		0.58	6.36	1.28
Pend d'Oreille (2007)	1145–1330	SW	SiL	880	4		1.08	0.14	0
Terrace Mtn (2009)	1000–1100	W	SL	550	3	0.70	0.31	0.02	

1. Site data are for the vicinity of plots, not for the entire fire.
2. SL = sandy loam; SiL = silty loam.
3. Mean annual precipitation estimated from PRISM climate data grid (Spittlehouse, 2006).
4. Number of untreated erosion plots in each fire. All plots were in areas of high soil burn severity.

In each study area, silt fence erosion plots were installed to measure soil erosion in burned areas. Other installations in the study sites included rainfall simulation experiments to study soil erosion under high rainfall intensity conditions (Covert & Jordan, 2009), a network of raingauges, and transects to sample soil moisture, soil burn severity and water repellency.

The silt fence plots used the design of Robichaud & Brown (2002), and were installed for the original purpose of evaluating the effectiveness of mulch treatments which were applied on portions of two fire impacted slopes. In this paper, only the data from untreated plots are reported. Each silt fence plot was 3–5 m wide, and 12–16 m long. Hillslope angles on which they were installed ranged from 31 to 90%. Several times each season, including after the snowmelt period and after each major rainfall event, sediment was removed from the silt fences and weighed, and a sample was returned to the laboratory for dry weight measurement and further analysis.

The Sitkum fire burned 39% of the drainage area of Sitkum Creek, a community watershed supplying about 25 homes on an alluvial fan on Kootenay Lake. This fire was therefore considered to be high risk with respect to water quality and potential flood damage. A stream gauging station was established at the fan apex in April 2008, and an Isco 6700 automatic pump sampler was installed and operated from April to October for four years after the fire. It was programmed to take daily samples during the spring freshet period, and every three days at other times. Samples were analysed for turbidity using a Hach 2100N turbidimeter, and for suspended sediment concentration if they exceeded a threshold turbidity of 1 NTU.

A nearby stream, Redfish Creek, is very similar to Sitkum Creek in drainage area, topography, geology and soils. It has been a BC Forest Service research watershed since 1992, and at the time of the fire in 2007, it had 34 years of streamflow data and 15 years of turbidity and sediment data. It was used as a reference watershed to investigate the effects of the fire on streamflow, suspended sediment and water quality in Sitkum Creek. As forest fires cannot be planned, it is rarely possible to set up a controlled experiment to investigate such changes. It cannot be established with any certainty that pre-fire hydrological conditions in the two watersheds were the same, but in this case we believe that they are reasonably similar. Figure 2 provides a map of the two watersheds, based on a satellite image.

Redfish Creek and Sitkum Creek have similar drainage areas, 27.2 and 27.0 km^2 respectively. Both Sitkum and Redfish creeks are underlain by granite of the Nelson batholith, and have similar soils derived from glacial till and colluvium of granitic origin. Redfish Creek has several small lakes, which Sitkum Creek lacks. They drain mountainous terrain, and above the main valley bottoms most precipitation falls as snow. The runoff regime is strongly nival, with most of the annual runoff occurring in the spring and early summer. Winter flows are consistently low. The elevation ranges are very similar, 700–2370 m for Redfish Creek and 600–2340 m for Sitkum Creek; Redfish Creek has a slightly higher elevation distribution and therefore probably receives more snow. A potential important difference is that the Redfish Creek watershed has a history of forest development and is about 12% logged, while Sitkum Creek has had relatively little logging. However, the Sitkum Creek watershed contains an abandoned gold mine and mill, which was in production until 1948, with some exploration activity in the 1980s (BC Min. Energy & Mines, Minfile Mineral Inventory, http://minfile.gov.bc.ca/Summary.aspx?minfilno=082FNW127). The ruins of the mill burned in the fire, which led to some concern that heavy metal contamination could be a possibility. In addition to the stream gauging station near the mouth of Sitkum Creek, three small tributaries were identified, two within and one outside the burn, and V-notch weirs with water level recorders, pump samplers, and bedload traps were installed in August 2008.

Water quality sampling was undertaken in 2008 on Sitkum and Redfish creeks as part of a separate one-year project of the University of British Columbia (UBC), to investigate water quality indicators, at a province-wide scale, which may be relevant to mountain pine beetle infestation and other disturbances in community watersheds (Brown *et al.*, 2011). Samples were collected weekly during the spring freshet period, and monthly during the summer and autumn. The samples were analysed for nutrients, metals, and total organic carbon (TOC) at the soil science lab at UBC. Details of the equipment and methods used for analyses are given in Brown *et al.* (2011). In 2009 and 2010, a similar sampling programme was continued on Sitkum and Redfish creeks as part of

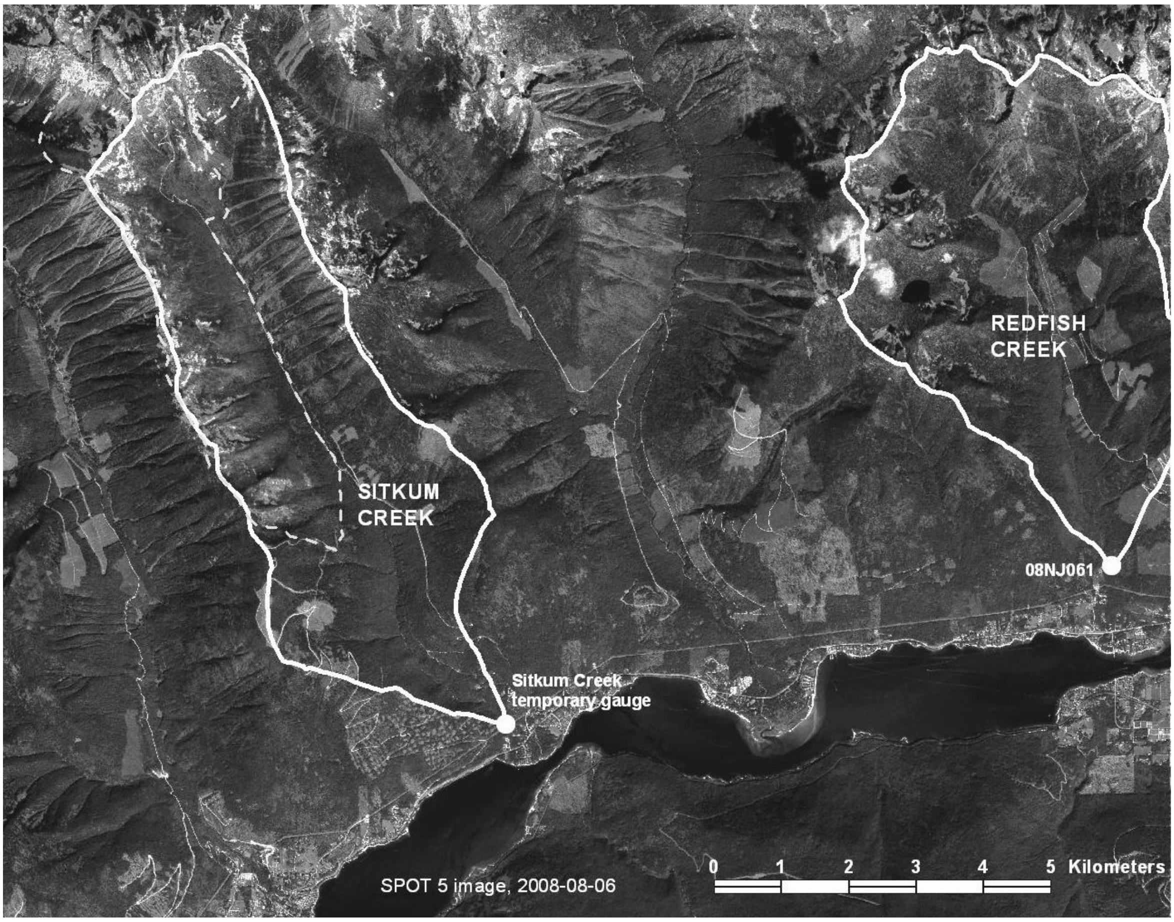

Fig. 2 Satellite image, showing the Sitkum Creek and Redfish Creek watersheds, and the locations of stream gauging stations. The extent of the 2007 Sitkum fire is outlined with a dashed line.

the present study. In 2009, samples were again analysed in the soil science laboratory at UBC. In 2010, this laboratory was not available, and samples were analysed for nutrients and TOC at a different laboratory at UBC, using similar methods and procedures. Unfortunately, inconsistencies in the 2010 data suggest that these results may not be reliable.

RESULTS

Soil erosion, turbidity and suspended sediment

A summary of sediment yields from the hillslope erosion plots is given in Table 1. These show a typical pattern of maximum erosion in the first year after the fire, with declining sediment yields each year thereafter as vegetation becomes established in the burned areas (Covert, 2010). The “0 years” data are for silt fence plots installed soon after the fire was out and sampled the same season; there was only one to two months after the fire until the first winter snow fell, and we had time to sample only two of the four fires.

These sediment yield results are generally lower than those reported elsewhere. In the western USA, a review by Moody & Martin (2009) showed that the highest post-wildfire sediment yields were at sites in Arizona and southern California, which also experience the highest short-term rainfall intensities. The lowest post-wildfire sediment yields and rainfall intensities were found in the “sub-Pacific” (or intermontane) region, which if extended north, would include the southern interior of BC. Other erosion plot results from the northernmost intermontane region in the USA (e.g. Robichaud *et al.*, 2009) are, on average, similar to the results from the present study. It should be noted that in this study, no rainstorms occurred in which short-term rainfall intensities (10 to 60 min) exceeded the 2-year return period.

At Sitkum Creek, the sediment yield results are anomalous, as the highest yields were measured in the second year. Visual observations of the plots indicated that a reason for this might be that much of the eroded sediment moved only a short distance downslope, and was then remobilized in subsequent rainfall or snowmelt events; it is likely that most erosion during the first year occurred in the upper part of the plots and did not reach the silt fence until the second year. The slope of the Sitkum plots was 31 to 38%, lower than the slopes of plots in the other fires, which ranged from 38 to 90%. Although there were only two plots installed in the Sitkum fire (there was no road access, and the sites required helicopter support to install and a long hike for each measurement), reconnaissance observations indicated that the results from these two plots were typical of erosion that occurred throughout the high-severity burn area.

In the three years following the 2007 fires, only one summer rainstorm occurred, on 19–21 August 2008, which produced enough runoff to cause a significant rise in the hydrographs of gauging stations in the region. At Sitkum Creek, there was 75 mm of rain in three days; the 24-h rainfall of 48 mm was about a 10-year event, but shorter-duration rainfall intensities were less than the 2-year return period. Although most of the soil erosion for the year probably occurred in this storm, the Sitkum Creek silt fences collected very little sediment (only 0.3 Mg/ha). However, the following year they collected much more (6 Mg/ha) even though there were no large rainstorms that summer. This supports the observation that most eroded sediment moved only a short distance downslope during each individual runoff event.

In the August 2008 rainstorms, on the two small tributary catchments of 48 and 64 ha draining the burned area, the automatic pump sampler collected samples every 2 hours, which with the continuous discharge data, enabled the suspended sediment yield for the storm to be calculated. The storm runoff was about 2 mm, less than 3% of the rainfall. The sediment yields for the two streams were 0.0005 and 0.0008 Mg/ha, at least three orders of magnitude lower than the surface erosion that probably occurred on severely burned sites during the storm. These results demonstrate that very little overland flow occurred in the burned area during this rainstorm, and that an insignificant amount, if any, of the eroded sediment reached the stream channels.

The stream gauges and pump samplers on Redfish and Sitkum creeks enable the calculation of approximate sediment yields for the two watersheds. The hydrographs, turbidity data, and annual sediment yields for 2008–2010 are shown in Fig. 3. In 2008, the suspended sediment yield for Sitkum Creek was 0.12 Mg/ha, which is almost three times the yield for Redfish Creek, although it is much lower than typical plot-scale sediment yields in the burned area. The turbidity data show that in 2008, Sitkum Creek had higher turbidity for much of the year, although turbidity on either creek rarely exceeded the common objective for domestic water sources of 5 NTU. In May 2008 (the exact date is unknown), a small landslide occurred on the mining road below the fire. It was probably caused by elevated groundwater levels below the burned area, and contributed some sediment (estimated as less than 100 m^3) to the creek. This event was probably responsible for the elevated turbidity in Sitkum Creek in May 2008. Another source of turbidity, especially later in the summer, may have been fine, burned, organic fragments from the burned area which were observed to accumulate in pools in the creek channel.

In 2009, the suspended sediment yield for Sitkum Creek was only slightly higher than for Redfish Creek, and except for isolated samples, turbidity on either creek rarely exceeded 5 NTU. In 2009, there were two significant sources of sediment in Sitkum Creek other than the fire. One of these was erosion of the road which was used for salvage logging in the summer of 2009, and contributed noticeable amounts of fine sediment to the creek as a result of maintenance and log hauling during wet weather. The other source was several large snow avalanches, which carried forest debris into the creek channel and created several log jams. In 2010, the suspended sediment yield for Sitkum Creek was double that of Redfish Creek. Considering the possible non-fire sediment sources, this may or may not be attributable to post-wildfire effects. It is possible, since late spring and summer flows in 2009 were very low, that sediment stored along the creek channel and in ephemeral headwaters channels in the first two years after the fire may have been remobilized by higher flows in 2010.

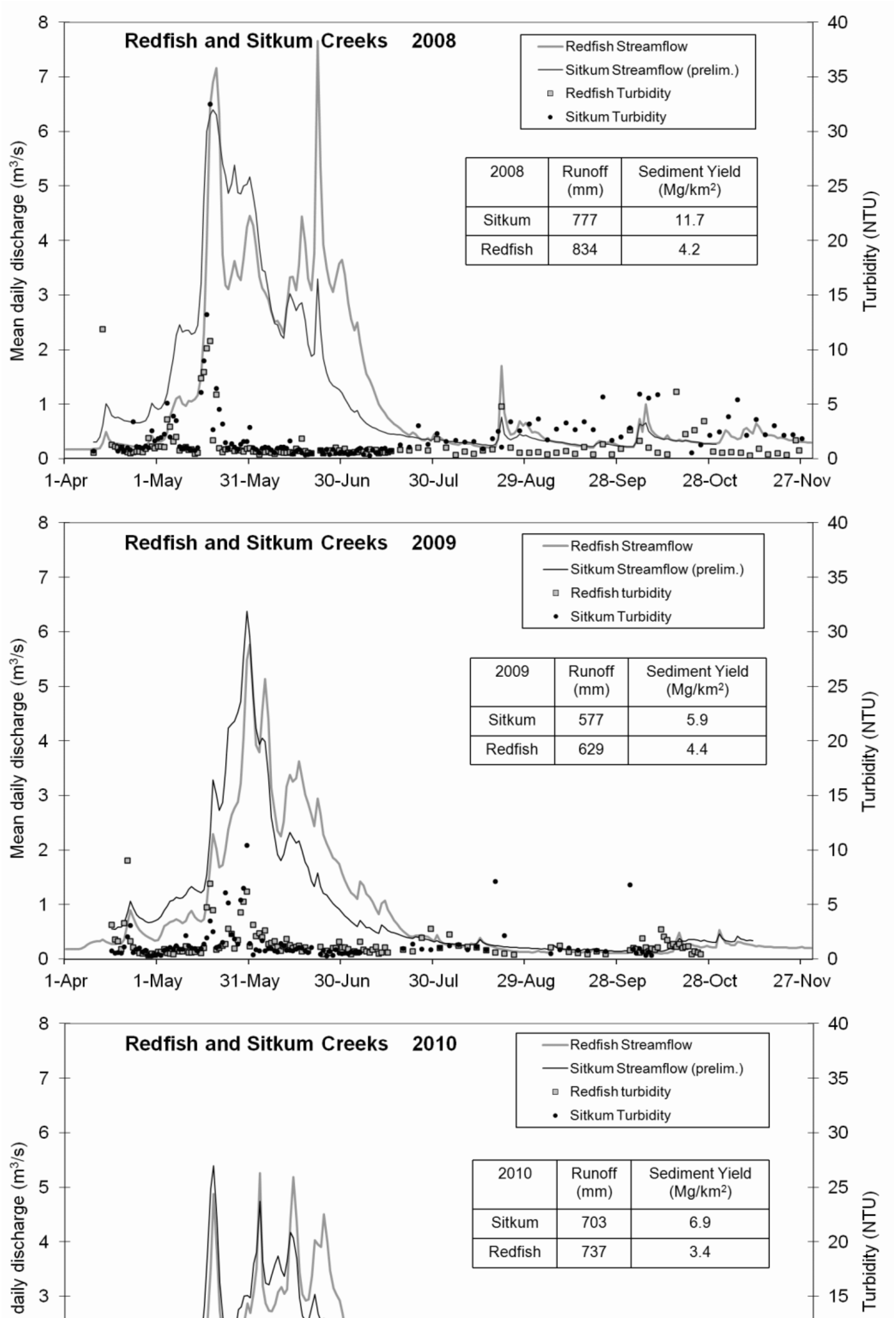

Fig. 3 Discharge hydrographs for Redfish and Sitkum Creeks for the first to third years after the Sitkum fire, showing turbidity samples collected on the two creeks, and calculated runoff and suspended sediment yields.

CHEMICAL WATER QUALITY

Nitrogen (NO_x-N) was the only chemical water quality parameter which showed a significant difference between Sitkum and Redfish creeks. In 2008 and 2009, NO_x-N concentrations were about two to five times higher in Sitkum Creek, with the highest concentrations occurring in early spring and in late summer to autumn. These differences are consistent with other studies (Gluns & Toews, 1989; Bladon *et al.*, 2008; and others reviewed by Neary *et al.*, 2005) which have commonly reported increased nitrogen levels for several years after wildfire. In 2010, the NO_x-N data are less consistent, but still show slightly higher average concentrations for the year in Sitkum Creek. All NO_x-N concentrations were far less than the drinking water guideline of 10 mg/L.

Figure 4 shows the NO_x-N data, and Table 2 gives summary data for selected water quality parameters. No statistical tests were performed, as there is no replication or pre-fire data which could enable statistical comparison. Phosphorus (PO_4) showed no consistent difference between the two creeks, and most readings were close to, or below, the limit of detection. Total organic carbon (TOC) was inexplicably higher in Redfish Creek, although the difference is probably not meaningful. Calcium and sodium concentrations, pH, and electrical conductivity, were not noticeably different between the two creeks. Heavy metals showed little difference between the creeks (copper and iron were slightly higher in Redfish Creek); all concentrations were well below drinking water guidelines. Arsenic and lead (possible contaminants from the Sitkum Creek mine) were below detectable levels. The small differences between the creeks in parameters other than nitrogen and TOC can probably be attributed to minor differences in bedrock geology.

The results for parameters other than nitrogen differ from the other two studies from western Canada; both Gluns & Toews (1989) and Bladon *et al.* (2008) reported increased post-wildfire phosphorus concentration, and the former study also reported increased alkalinity and hardness. There is little information available on the effects of wildfire on releases of heavy metals (Neary *et al.*, 2005).

Table 2 Chemical water quality: mean, maximum, and standard deviation for selected parameters.

	Turbidity (NTU)	Conductivity (µS/cm, 25°C)	pH	NO_x-N (mg/L)	PO_4 (mg/L)	TOC (mg/L)	Ca (mg/L)	Na (mg/L)
Detection limit	0.2	– [1]	–	0.02	0.01		0.007	0.1
2008: n [2]	116	11						
Redfish: mean	1.12	23.6	6.81	0.059	0.015	3.39	3.32	0.63
maximum	10.8	–	–	0.155	0.043	7.69	6.15	1.09
st. dev.	1.70	10.3	0.26	0.048	0.011	1.65	1.36	0.26
Sitkum: mean	2.12	27.6	6.76	0.104	0.011	2.60	3.79	0.71
maximum	32.5	–	–	0.392	0.032	5.01	5.09	1.39
st. dev.	3.40	8.7	0.28	0.136	0.010	1.05	1.10	0.29
2009: n	106	8						
Redfish: mean	1.43	31.2	7.13	0.022	0.004	2.66	4.11	0.39
maximum	9.0	–	–	0.037	0.006	4.04	6.16	0.54
st. dev.	1.40	12.2	0.47	0.015	0.002	1.06	1.89	0.15
Sitkum: mean	1.34	32.8	7.00	0.115	0.005	2.15	3.99	0.42
maximum	10.4	–	–	0.270	0.014	3.26	5.25	0.58
st. dev.	1.60	8.9	0.13	0.099	0.005	0.70	1.17	0.13
2010: n	97	6						
Redfish: mean	1.08	25.2	6.82	0.110	0.049			
maximum	6.6	–	–	0.263	0.169			
st. dev.	0.98	7.8	0.66	0.099	0.061			
Sitkum: mean	1.87	24.3	6.65	0.167	0.036			
maximum	7.9	–	–	0.548	0.100			
st. dev.	1.40	10.1	0.83	0.203	0.034			

1. "–" indicates not applicable.
2. Sample size (n) each year is the same for all parameters except turbidity.
3. Blank cells indicate data are not available for that year.

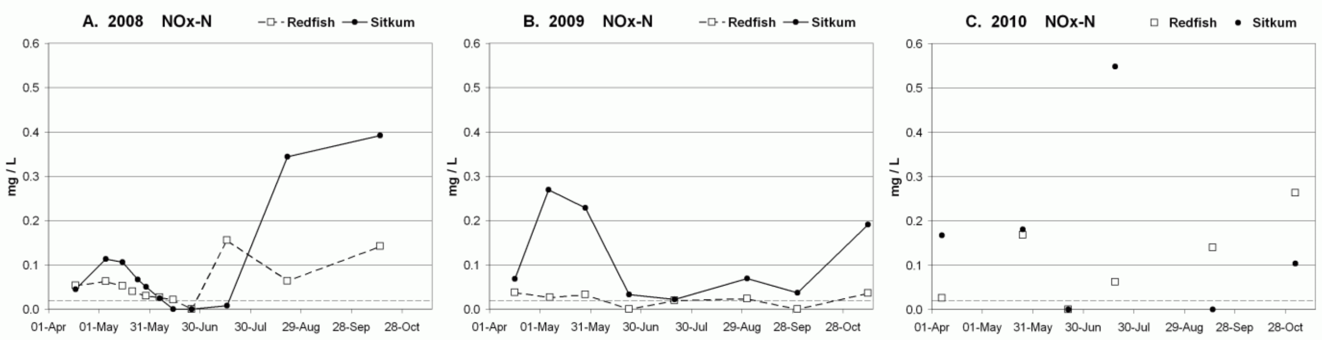

Fig. 4 Nitrate-nitrite (NO_x-N) samples collected on Sitkum and Redfish creeks, for three years after the 2007 Sitkum fire. Dashed line indicates the detection limit. (For 2010, no connecting line is shown, due to the lower frequency of sampling, and to one anomalous sample.)

ANECDOTAL ACCOUNTS OF POST-WILDFIRE IMPACTS ON WATER QUALITY

Sitkum Creek supplies water to a small community on its alluvial fan. The community water system consists of a water intake in the creek above the fan, and a sand-box filter to screen out debris and suspended sediment. Water from this filter then flows to an ultra-violet treatment facility. Regular water quality samples are collected at this facility, but not further upstream (D. Toews, Sitkum Creek Improvement District, pers. comm.). The only reported impact to the water supply was a greater than normal accumulation of suspended sediment and organic debris in the sand filter in 2008, which required more frequent back-flushing of the filter. In 2009, there was an unusual amount of debris in the filter, which necessitated replacement of the sand. As mentioned above, there were other sources of sediment in the water that year (road erosion and avalanches), so this sediment may not be entirely attributable to the fire.

There are two other cases in this region of large wildfires burning in community watersheds. The 2007 Kemp Creek fire burned about 20% of the community watershed supplying the village of Kaslo. The 2003 Kutetl fire burned about 10% of the drainage area of Five-Mile Creek, the main community watershed supplying the city of Nelson. In neither of these cases were there reports of increases in turbidity, other water quality effects, or physical impacts to the water intakes, affecting the municipal water supplies (G. Walker, public works foreman, Village of Kaslo, pers. comm.; G. Bogaard, utilities supervisor, City of Nelson, pers. comm.). These observations are in contrast with reports of large sediment yields following wildfire at some locations in the USA, especially Colorado and southern California (as reviewed by Moody & Martin, 2009). However, they are consistent with the general lack of reports of significant post-wildfire turbidity increases or other water quality impacts from water utilities in BC.

The summer following the 2003 Kuskonook fire near Creston, water users on Kuskonook Creek (a domestic watershed) noticed large quantities of a black substance in their water intakes. A month later, when the author and others investigated the large debris flow on Kuskonook Creek (Jordan & Covert, 2009) we observed areas where the wettable layer of burned surface soil had been eroded away, above a water repellent layer which was 1–2 cm below the surface. This fire exhibited strong and extensive water repellency, as did several other 2003 fires which burned under extreme drought conditions. The Kuskonook Creek example is the only case in this region known to the author where a significant water quality impact was reported following the 2003 or subsequent fires (and it became moot later that summer when the debris flow destroyed all water intakes on the creek). However, there is no systematic reporting or data collection of water quality on domestic watersheds, so it is possible that unreported cases of poor water quality may have occurred.

Our observations at Kuskonook Creek suggest that strong water repellency may be an important factor in the likelihood that burned surface soil and ash will be transported to stream channels during high-intensity rainfall events. The 2007 fires in this region, in contrast, had relatively sporadic water repellency, and also there were no high-intensity rainstorms in the three summers following the fires.

DISCUSSION AND CONCLUSIONS

Although significant plot-scale soil erosion, in the order of 1 to 10 Mg/ha, took place in the four fires examined in this study, it was much lower than erosion rates commonly measured at more southerly latitudes. At most sites, erosion rates dropped over two to three years, as the sites revegetated. Generally, revegetation occurred more rapidly on moist sites and at lower elevations (Covert, 2010), and erosion rates were accordingly lower on these sites. Since 2007, high-intensity short-duration rainstorms have been lacking; if such rainstorms had occurred within one or two years of the fires, it is likely that erosion rates would have been higher. After the 2003 wildfires in southern British Columbia, in the first year after the fire there were unusually abundant high-intensity rainstorms in the region, and as a result there were several severe landslide and flooding incidents.

In the 2007 Sitkum Creek fire, sediment yield measurements were made at two watershed scales, small (<100 ha) tributaries, and the whole catchment (27 km^2), and comparisons were made with the similar Redfish Creek watershed. For three years after the fire, both physical and chemical water quality impacts were minimal. At both scales, increases in turbidity and suspended sediment yield occurred in the first year after the fire, but these were slight, and comparable to increased erosion and sedimentation that typically is caused in this region by other disturbances such as logging and road building (Jordan, 2006).

One reason for the relatively slight impacts (compared with other regions at lower latitudes) of wildfire on erosion and sedimentation in the southern interior of British Columbia is the strongly nival runoff regime (Eaton *et al.*, 2010). The annual streamflow hydrograph for all but very small or low-elevation drainages is invariably dominated by snowmelt, and even with increased rainstorm runoff following wildfire, it is rare for discharge during summer events to approach the spring snowmelt peak. Therefore, entrainment of sediment from gully down-cutting and bank erosion is unlikely during summer rainstorm events. Also, at higher elevations, most precipitation falls as snow, and the snow-free season is only four to six months, so there is less time each year for rainfall events to occur than in regions with relatively little snow cover.

Another reason for the relatively low sediment yields observed in this study is that, across most of the landscape, the connectivity between hillslopes and stream channels is low. This may be a result of the glacial history of the region, which has resulted in many U-shaped or widened valleys and under-fit streams, in contrast to unglaciated, fluvially-dissected, landscapes. Qualitative observations in burned areas during this study suggested that in most locations, eroded sediment moved only a short distance downslope and was deposited behind obstructions, in stony areas, on gentler slopes in local valley bottoms, or behind rapidly-growing riparian vegetation.

These general conclusions about low sediment yields following fire must be qualified with the observation that, in susceptible terrain, the likelihood of debris flows and other landslides can be substantially increased by severe wildfire (Cannon & Gartner, 2005; Shakesby & Doerr, 2006; Jordan & Covert, 2010; Jordan, 2012). In this region, the increased landslide hazard is largely due to higher snow accumulation and snowmelt rates following wildfire, and consequent higher groundwater levels. If a debris flow occurs, inevitably there will be a significant impact on water quality, although this may be short-lived.

Chemical water quality impacts on Sitkum Creek, relative to Redfish Creek, were limited to an increase in nitrogen (as NO_x-N), consistent with measurements that have been frequently reported following wildfire elsewhere. Differences in other solutes were minimal or nonexistent, compared with a nearby unburned reference watershed. These results are consistent with conclusions reported elsewhere, that changes in post-wildfire chemical water quality are seldom a concern for potable water supplies; however, potential increases in turbidity and sediment yield should be considered in managing community water systems after wildfire.

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