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WILDFIRE EFFECTS ON THE QUANTITY AND COMPOSITION OF SUSPENDED AND GRAVEL-STORED SEDIMENTS

ELLEN L. PETTICREW[1,*], PHILIP N. OWENS[2] and TIMOTHY R. GILES[3]
[1]*School of Geography, University of Plymouth, Plymouth, UK*
[2]*National Soil Resources Institute, Cranfield University, North Wyke, UK*
[3]*British Columbia Ministry of Forests and Range, Kamloops, British Columbia, Canada*
*(*author for correspondence, Present address: Geography Program, University of Northern British Columbia, Canada, e-mail: ellen@unbc.ca; phone: +1-250-960-6645; fax: +1-250-960-6533)*

Abstract. In August of 2003 a severe wildfire burnt the majority of Fishtrap Creek, a 170 km^2 catchment in central British Columbia, Canada. The objective of this study was to determine the short-term (15-month) influence of the wildfire on the amount and composition of fine sediment delivery and retention in the system and to compare it to a similar unburnt catchment. In the spring of 2004 automatic water samplers were installed at a gauging site on Fishtrap Creek to collect suspended sediments from the snowmelt runoff and gravel traps were deployed on the channel bed surface to collect composite samples of suspended fine sediment. Jamieson, the reference creek, exhibits similar geology and pre-burn vegetation and was sampled in the same manner for comparison. Composite suspended sediment collected in the traps was removed from the streams in mid-summer and early September. Quantitative estimates of the amount and particle size structure of the naturally stored fine sediment in, and on, the gravel creekbed were obtained in pre-melt, mid and late-summer conditions. Estimates of suspended sediment yields indicated that while the burnt system delivered 66% more material per unit area, the total seasonal suspended sediment yield was low (855 kg km^{-2}) compared to other fire-disturbed systems. While the burnt catchment was primed to deliver sediment, the hydrologic drivers were not of sufficient magnitude to generate a substantial response, suggesting that in this first post-fire year the system was transport-limited, not supply-limited. Differences were noted in the spatial and seasonal composition of the <500 μm composite suspended sediments, with the burnt catchment having significantly ($P \leq 0.05$) more OM%. Seasonally a significant increase of OM% in late summer samples was associated with instream biofilms and possible delivery of black carbon. The system's post-fire response was not geomorphically substantial but significant biological differences were noted in the short-term.

Keywords: organic matter, sediment yield, sediment response, suspended sediment, wildfire

1. Introduction

Recently, there has been an increase in the number of studies concerned with the effects of fires, both natural (e.g., wildfires) and human induced (e.g., prescribed burning) in forested catchments. This interest is due to a variety of reasons including the effect of fires on forest ecosystems and the implications for resource management, and concerns associated with the likelihood of increases in the number of wildfires in some areas due to climate change. Within a geomorphological context, much of the research on the response of catchments to fires, and particularly wildfires, has focused on the impacts of fire on (a) soil hydrology and river flows, and (b) soil erosion, mass movement events and sediment fluxes in rivers (Shakesby & Doerr, 2006). Research on the latter has been concerned primarily with how rates of soil erosion and fluxes of sediment in rivers have responded to fire events. Most of the available evidence suggests that these rates and fluxes increase after fires as the bulk of the surface vegetation cover is removed and soil hydrology changes (e.g., due to an increase in soil hydrophobicity); consequently the soil is more susceptible to erosion, mass movement and bank erosion processes (e.g., Cerda & Lasanta, 2005). Studies generally show that this is the typical behaviour immediately following a fire and that, after the initial response, values tend to return to those similar to pre-fire conditions, with the time required ranging from a few years to decades (Shakesby & Doerr, 2006). Recently, research has also focused on changes in the properties of the burnt soil and the material delivered to, and transported by, rivers (e.g., Certini, 2005). This interest has developed from the recognition that it is the type and quality of the material that is being eroded, and thus lost from the soil profile, and supplied to rivers (such as trace element, nutrient and organic matter/carbon content, and particle size composition), in addition to actual amounts of sediment, that are important for the future ability of soils to support vegetation and for water quality and aquatic ecology. Studies have tended to document a change in the nutrient, organic matter content and particle size content of mobilized and transported sediment following fire (Certini, 2005).

This paper presents preliminary (i.e., first 15 months) results from an investigation into the effects of a wildfire on a mixed coniferous catchment in British Columbia, Canada. The aims were to determine:

1) the post-fire response of a) suspended sediment fluxes and b) storage of fine-grained sediment within channels;
2) if there was a change in the compositional properties (e.g., organic matter content and particle size) of the transported and stored sediment due to the wildfire.

2. Materials and Methods

In August 2003, severe wildfires burnt in many locations across British Columbia (BC), Canada with the McLure fire, in the central interior of BC, burning an area of ca. 260 km^2. The Fishtrap Creek catchment, forested with Pines, Firs, Spruce and Cedar, was severely burnt in the lower reaches and moderately burnt in the headwaters. The Jamieson Creek catchment, located ca. 15 km to the south of Fishtrap, was not affected by the McLure fire and as it has similar vegetation cover, topography, stream slopes, precipitation regime and geology as Fishtrap, it serves as a reference catchment for comparing the effects of the McLure fire. The catchments have a distinct snowmelt regime with melt typically starting in early April and the main flood discharge occurring in mid May.

An automatic ISCO water sampler was installed on March 29, 2004 at Fishtrap Creek (~120°15′ WL: 51°10′ NL) to collect 1 L suspended particulate matter (SPM) every 4 h from 135 km^2 of catchment above this station. High frequency sampling continued until the snowmelt freshet was completed and on June 18 sampling was reduced to 8 h intervals. Collection continued until Oct 22, 2004. Another ISCO water sampler was installed on April 14, 2004 on the lower reaches of Jamieson Creek (catchment area of 215 km^2; ~120°15′ WL: 50°55′ NL) and water was collected on the same schedule as in Fishtrap. Continuous discharge was measured just downstream of the sample site on Fishtrap while for Jamieson it was calculated from the Fishtrap data set using areal proportions. Specific sediment yields (kg km^{-2}) were determined for the ~7-month sampling season. Precipitation data were obtained from the nearest Environment Canada meteorological station in Kamloops, approximately 30 km south of the sites.

Six gravel tube traps (Biickert, 1999) were installed in Fishtrap on April 13, 2004, with a set of three in an upstream riffle and a second set downstream. Another six were installed in two riffles in Jamieson on April 14. The upstream and downstream sites in each system were selected to have comparable flow regimes although several traps had to be moved to deeper water as the season progressed and discharge dropped. Each tube trap (45 cm long and 7.5 cm diameter) was filled with clean gravel which were contained by wire mesh at each end. Three tubes were fixed in place on the stream bed, parallel to each other and facing into the flow. They were left to collect any actively transported sediment smaller than the grid size of 0.64 cm, until June 23, 2004. When the tubes were retrieved the sediment <0.64 cm was washed from the trap gravels and collected in buckets for processing. The cleaned traps were replaced in the same locations and collected sediment until September 1, 2004.

In the field, the buckets containing both trap sediment and wash water were used to obtain an estimate of sediment less than approximately 500 μm. This size category was selected operationally as the triplicate 50 ml sub-samples were collected from the top few centimetres of the total sample a few seconds following stirring. The maximum size of sediment collected would be <500 μm, due to the settling speed of particles larger than this. These samples, in conjunction with the water volume, were used to calculate the mass of trapped sediment <500 μm. The material remaining in the buckets was transported back to a laboratory, air dried and amalgamated to obtain the total mass collected by the traps. Organic matter (OM) content of the total mass and <500 μm sub-samples was determined by ashing replicates in a muffle furnace at 550 °C. A sub-sample of the total mass was dry-sieved through a 500 μm mesh, the organic matter removed using hydrogen peroxide and particle size analyses of the inorganic trap sediments were undertaken using a Malvern laser particle sizer.

In April, June and September, when the gravel trap sites were visited, a quantitative estimate of the amount of naturally stored fine sediment was determined using a cylinder resuspension technique (Petticrew, Krein, & Walling, 2006). The mass of sediment stored on 531 cm^2 of gravel surface (as determined by the area of the cylinder base) was estimated by resuspending it with a gentle stirring of the water in the cylinder. Three 1 L samples of the mixed water were taken for analysis of resuspended sediment and organic matter content. Water volumes in the cylinder combined with the resuspended sediment concentration allowed an estimate of the areal load of surface-stored fine sediment. Mixing the gravel at the base of the cylinder to a depth of 15 cm, and sub-sampling the turbid water above allowed an estimate of the areal load of gravel-stored fine sediments. Resuspended sediment concentrations were obtained by filtering the water through pre-ashed and pre-weighed GF-F filters. Organic matter content was determined by ashing the dried filters at 550 °C in excess of 1 h. Due to small sample sizes (n=4–6), tests of significant differences were determined using the non-parametric Mann–Whitney test at 95% confidence limits.

3. Results and Discussion

3.1. Suspended Sediment Loads and Yields

Seasonal sediment loads, yields and denudation rates for both of the catchments are presented in Table I. The burnt basin has slightly higher SPM and inorganic seasonal loads even though the unburnt Jamieson is 80 km^2 larger. When the seasonal yields are compared the burnt basin contributes ~66% more sediment per unit area. The specific particulate sediment yields (kg km^{-2} day^{-1}), calculated from the average daily SPM (combined organic and inorganic) loads, are shown over the approximately seven month sampling period for both creeks in Figure 1. The spring-melt freshet in the burnt catchment (Fishtrap) carries the bulk of the seasonal material, with the maximum yield occurring on April 15 (day 106). In Jamieson this represented our second day of sampling, but a flush of sediment occurred 15–20 days later, in early May (days 121–126) likely reflecting delayed snowmelt in the unburnt basin (Figure 2). These differences in snowmelt timing are corroborated by comparisons of snowmelt patterns and rates between the burnt headwaters of Fishtrap Creek and an adjacent forested system (R.D. Winkler, personal communication) which indicated that the snowpack of the burnt area had 42% increased water equivalent on March 9, 2004 and that snowmelt was completed three weeks earlier in the burnt *versus* the forested

TABLE I

Estimates of seasonal loads, yields and denudation rates for both suspended particulate matter (SPM) and inorganic sediment for Fishtrap and Jamieson Creeks (2004). Values determined using an 18-day delay in springmelt discharge in Jamieson are presented to allow comparison

Parameter calculated	Fishtrap Creek (burnt)	Jamieson Creek (unburnt)	Jamieson Creek (18-day springmelt discharge delay)
Seasonal SPM load (kg)	115,360	110,952	108,025
Seasonal inorganic load (kg)	71,595	69,674	67,629
Seasonal SPM yield (kg km^{-2})	855	516	502
Seasonal inorganic yield (kg km^{-2})	530	324	314
Denudation (SPM[a]) (μm)	0.53	0.32	0.31
Denudation (inorganic[b]) (μm)	0.21	0.13	0.13

[a]Density of 1.6 assumed
[b]Density of 2.5 assumed

areas. As the suspended sediment concentrations (Figure 2) and visual field evidence suggest that the spring freshet occurred in Fishtrap approximately 18 days earlier, an underestimate of spring-melt discharge for Jamieson would result from the use of an areal discharge relationship between basins. Therefore another estimate of discharge, loads and yields were made using an 18-day delay for spring-melt discharge values for Jamieson. Results indicated that the seasonal estimates calculated both ways (Table I) are similar in magnitude, even though their timing would be slightly altered. In any case, for both scenarios the loads, yields and denudation rates for the unburnt basin are likely to be overestimates, as at pre-melt the burnt basin was observed to have a great water equivalent than unburnt areas. This means the range between the burnt and unburnt catchments noted in Table I are conservative estimates of the difference in the geomorphic response of the two systems.

While the values of the seasonal yield in the burnt catchment are larger than the estimates for the undisturbed, forested catchment, the magnitude of Fishtrap's yields are low in comparison to other burnt systems (Shakesby & Doerr, 2006). Helvey (1980) reported post-fire sediment yields of 500 kg km^{-2} over six months for a moderate burn and 12,000 kg km^{-2} yr^{-1} for an intense burn in mixed coniferous forests in Washington, USA. Given that the lower portion of Fishtrap was severely burned, as evidenced by a surface cover of ash, burnt debris and large areas of exposed topsoil (Owens, Blake, & Petticrew, this issue), the sediment yields are surprisingly low for a system so primed for erosion. Inorganic denudation rates of 0.2 (burnt) and 0.1 (unburnt) μm yr^{-1} are also low for

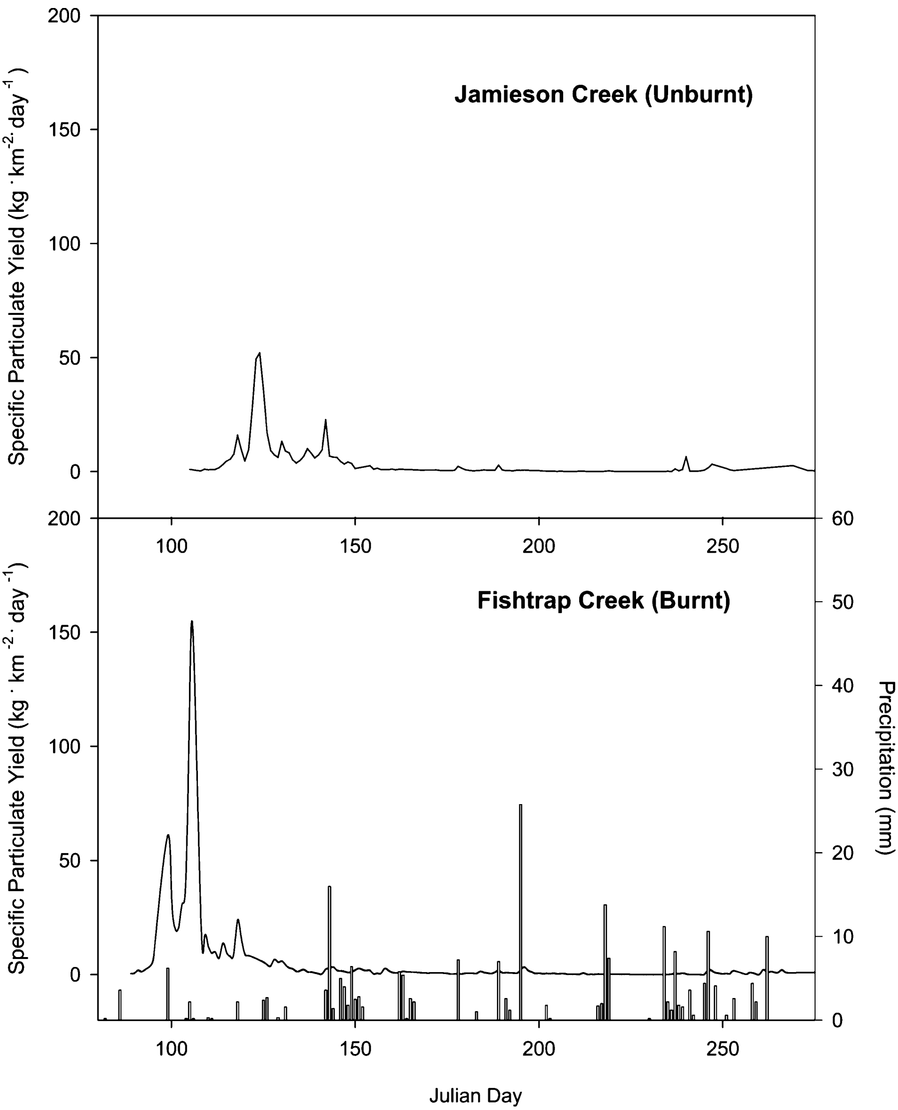

Figure 1. Specific particulate yields for the burnt (Fishtrap, 135 km^2) and unburnt (Jamieson, 215 km^2) catchments. The spring-melt yield for Jamieson has been calculated using an 18-day offset to account for the delayed snowmelt in the unburnt basin.

catchments of this size and are especially low for a disturbed system (e.g., Caine, 2004). These data all suggest that while a ready supply of sediment was available in the burnt catchment in 2004, the driving agents (precipitation and spring-melt discharge) did not move much material in the 15-month period following the McLure fire.

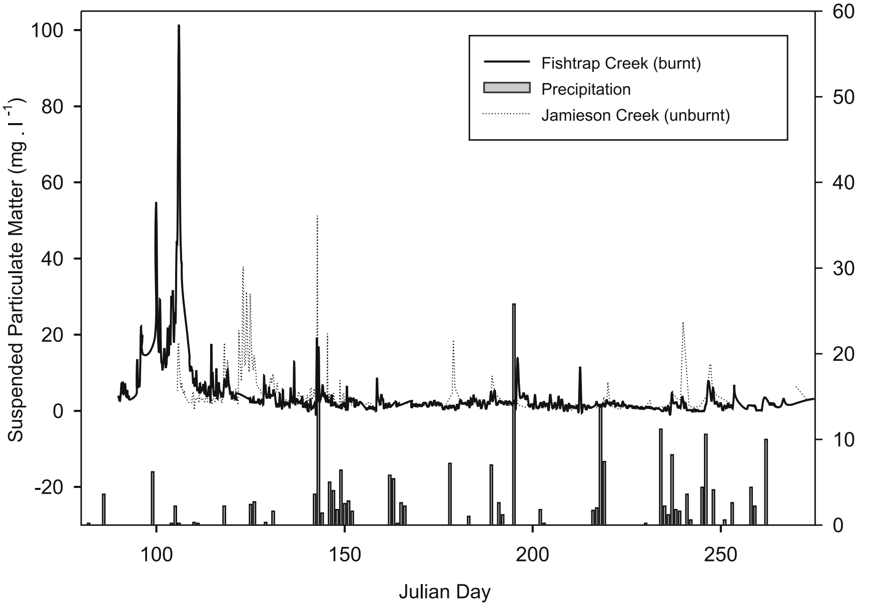

Figure 2. Total SPM in Fishtrap Creek (burnt), from March 30 to Oct 22, 2004 and SPM for Jamieson Creek, (unburnt) from April 14 to Oct 22, 2004. Daily precipitation data for Kamloops, British Columbia are shown.

3.2. Sediment Transport and Composition

The total mass of sediment collected in the gravel traps for both periods in the burnt catchment was almost double that of Jamieson (Table II) but these values should not be equated, as the total flow though the tubes varied between trap sites. However, the proportional composition of the sediment <500 μm can be compared and indicates a significantly ($P<0.05$) higher amount of OM% in the burnt system's traps for both seasons (Table II). As well, in both catchments the late summer traps exhibit significantly ($P<0.05$) higher percentage of OM values than the material collected over the spring and early summer. These spatial and temporal differences in OM likely reflect both instream and terrestrial processes. What was apparent in the streams when the gravel traps were being retrieved on June 23 and again on September 1 was an instream cover of benthic biofilms on the gravels in Fishtrap. The lack of canopy cover, due to the fire, allowed increased light which facilitated periphytic algae growth, as observed in recently harvested creeks (Fuchs, Hinch, & Mellina, 2003). These biofilms degrade and are flushed downstream episodically and likely represent a portion of the increased trap OM content. Another explanation for this OM increase in Fishtrap is the transport of 'black carbon' in the stream as suspended sediment. These particles are products of incomplete combustion of organics (Certini, 2005) and due to their low density

TABLE II

Mass of total and <500 μm sediment collected in surface traps and the proportion of organic matter in the burnt (Fishtrap) and unburnt (Jamieson) catchments (2004). The percentage of sand, silt and clay in the <500 μm fraction is also presented with one standard deviation (n=5 or 6) shown in brackets

	Total trap sediment (g)	Total trap organic matter (%)	Trap sediment <500 μm (%)	Trap organic matter <500 μm (%)	Absolute particle size <500 μm		
					% sand	% silt	% clay
Fishtrap							
June	991.8	8.3	39.0	18.0 (1.6)	34.6 (6.0)	60.6 (5.8)	4.8 (0.1)
Sept	592.8	14.3	39.7	29.9 (2.1)	36.1 (8.5)	59.2 (8.1)	4.7 (0.4)
Jamieson							
June	577.2	7.4	69.3	13.1 (1.8)	28.2 (3.7)	64.9 (3.2)	6.9 (0.5)
Sept	319.9	9.5	50.6	19.2 (2.2)	11.7 (3.0)	79.6 (2.3)	8.7 (0.7)

would be easily entrained as suspended sediment. Future microscopy and particle density analysis of the trap samples should elucidate these possibilities.

3.3. Fine Sediment Storage: Amounts and Composition

Table III represents the areal loadings of surface and gravel-stored (15 cm depth) fine sediments. There are no statistically significant differences in the seasonal patterns observed in either stream, and no major statistical differences in the amount of stored sediment between streams. While high variability exists in the OM% of these naturally-stored sediments, we do see a pattern of increasing OM (increases of >25%) in the surface sediments as the season progresses in Fishtrap, but not in Jamieson. June and September surface samples in Fishtrap have higher average and standard deviation values than the sediments stored in the top 15 cm of gravels, indicating the presence and the spatial patchiness of the benthic biofilms and/or the delivery of black carbon particles moved off the watershed in spring-melt and rainstorms in the burnt system.

4. Conclusions

The suspended sediment loads, yields and denudation rates of Fishtrap Creek, a burnt 135 km^2 catchment, were greater than those of unburnt Jamieson Creek, a larger (215 km^2) but biogeochemically similar, nearby catchment. While the differences in the response of the disturbed and undisturbed forested system were apparent, and potentially underestimated, the magnitude of the response to severe

TABLE III

Amount of sediments stored on and in the gravel bed, and the proportion of sediment organic matter for the burnt (Fishtrap) and unburnt (Jamieson) catchments (2004). n=4, standard deviation in brackets

	Areal load (mg cm^{-2})		Organic matter percentage	
	Surface	Top 15 cm gravel	Surface	Top 15 cm gravel
Fishtrap				
April	2.6 (1.3)	12.3 (9.1)	21.4 (2.1)	18.5 (4.5)
June	2.3 (2.1)	9.7 (9.3)	31.9 (23.3)	18.0 (4.8)
Sept	1.4 (1.5)	22.6 (16.5)	48.6 (23.3)	21.7 (5.3)
Jamieson				
April	2.4 (2.2)	7.7 (6.4)	24.4 (3.5)	12.8 (0.6)
June	1.6 (0.3)	20.0 (5.6)	26.2 (5.1)	12.4 (2.3)
Sept	3.7 (0.9)	23.0 (6.5)	22.0 (3.7)	15.6 (1.6)

wildfire was relatively small. Similarly, there were no significant differences in the amount of material stored on, or in, the channel bed. The lack of a significant first spring-melt response in sediment fluxes and channel storage in the Fishtrap catchment is somewhat surprising and suggests that there has been no major short-term response to the wildfire during the first 15 months, at least in terms of sediment flux. It is clear from visual observations that the catchment surface of Fishtrap was susceptible to surface erosion processes (Owens et al., this issue). However, the magnitude of response indicates that surface, channel and bank erosion was minimal during snowmelt and that the rainfall events over this time were not sufficient to initiate substantive erosive flows. Thus, while the catchment surface is primed for erosion and sediment transfers, the hydrological drivers required for significant inorganic sediment redistribution were not in operation. In a recent review paper Shakesby and Doerr (2006) indicate the need for a clear measure of the degradational significance of post-fire soil losses. In this case, the calculations for the burnt watershed indicate the first year response, seen in many other case studies, is muted due to transport-limiting factors rather than supply limitation. There is clearly a need for continued monitoring in these systems to determine when, and indeed if, Fishtrap will respond to the severe wildfire of summer 2003.

In contrast, the organic matter content of the smaller-sized sediment actively being transported in Fishtrap is significantly greater than in Jamieson. Thus, although there is a limited amount of available inorganic sediment being transported to, and in, the burnt river system, there is clearly a difference in the composition of sediment being mobilised and redistributed, reflecting processes on the land (e.g., an increase in exposed burnt soil that could contribute black carbon) and in the channel (e.g., biofilm growth and die-off). The temporal and spatial differences in the organic material and the lack of noteworthy transfers of inorganics suggests that this burnt system is biologically, but not geomorphically responsive in this short-term post-fire period.

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