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The use of composite fingerprints to quantify sediment sources in a wildfire impacted landscape, Alberta, Canada

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HIGHLIGHTS

- A tracing procedure is used to apportion sediment sources in a wildfire landscape.
- Sources are represented by unburned, burned and burned–salvage logged areas.
- Source proportions are estimated at 17% (unburned), 45% (burned) and 38% (burned–salvage logged).

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ABSTRACT

There is increasing global concern regarding the impacts of large scale land disturbance by wildfire on a wide range of water and related ecological services. This study explores the impact of the 2003 Lost Creek wildfire in the Crowsnest River basin, Alberta, Canada on regional scale sediment sources using a tracing approach. A composite geochemical fingerprinting procedure was used to apportion the sediment efflux among three key spatial sediment sources: 1) unburned (reference) 2) burned and 3) burned sub-basins that were subsequently salvage logged. Spatial sediment sources were characterized by collecting time-integrated suspended sediment samples using passive devices during the entire ice free periods in 2009 and 2010. The tracing procedure combines the Kruskal–Wallis H-test, principal component analysis and genetic-algorithm driven discriminant function analysis for source discrimination. Source apportionment was based on a numerical mass balance model deployed within a Monte Carlo framework incorporating both local optimization and global (genetic algorithm) optimization. The mean relative frequency-weighted average median inputs from the three spatial source units were estimated to be 17% (inter-quartile uncertainty range 0–32%) from the reference areas, 45% (inter-quartile uncertainty range 25–65%) from the burned areas and 38% (inter-quartile uncertainty range 14–59%) from the burned–salvage logged areas. High sediment inputs from burned and the burned–salvage logged areas, representing spatial source units 2 and 3, reflect the lasting effects of forest canopy and forest floor organic matter disturbance during the 2003 wildfire including increased runoff and sediment availability related to high terrestrial erosion, streamside mass wasting and river bank collapse. The results demonstrate the impact of wildfire and incremental pressures associated with salvage logging on catchment spatial sediment sources in higher elevation Montane regions where forest growth and vegetation recovery are relatively slow.

1. Introduction

The frequency and severity of large-scale natural disturbances such as wildfire in forested regions of North America have significantly increased in recent decades, primarily due to warmer spring and summer temperatures and drought (Flannigan et al., 2009, 2013; Westerling et al., 2006, 2011). Because of the severity and magnitude of many wildfire related disturbances, sediment fluxes (Moody and Martin, 2001; Blake et al., 2005; Silins et al., 2008, 2009) can be modified at rates and magnitudes that often cause profound and long lasting changes in river system function (DeBano et al., 1998; Bladon et al., 2008), geomorphology (Moody and Martin, 2001) and water quality (Blake et al., 2005, 2007, 2009a). Thus, the increasing occurrence of wildfires in many regions of the globe has important implications for regional water resources (Smith et al., 2010) including the need for adaptive strategies for protecting source water supplies (Emelko et al., 2011).

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Given the increasing concern about wildfire driven landscape disturbance on a range of water services worldwide, there is a commensurate need to investigate the source, transport and fate of pollutants, including sediment, in order to make scientifically sound land management decisions. While a growing number of studies have reported on post-fire sediment production at small–medium watershed scales (<10–20 km^2), far fewer studies have documented the effects of landscape disturbance by wildfire on sediment contribution or the implications of upstream wildfire associated sediment loading into larger river systems. Because a wide range of contaminants are both transported through, and stored in, river channels in association with sediment, understanding sediment sources is key to informing the evidence base on the movement of contaminants at large basin scales (Horowitz and Elrick, 1987; Ongley et al., 1992). Thus, insights into how wildfire affects the primary sources of sediment and associated contaminants are necessary in understanding how these disturbance types affect ecosystem function and a wide range of human water uses downstream of these disturbances.

In recent years, a variety of source fingerprinting techniques have been developed and successfully used to quantify sediment provenance at catchment scale (Collins and Walling, 2004) and to examine linkages between erosion patterns and land use change (Huang and O'Connell, 2000) or the occurrence of extreme flood events (Collins et al., 1997). Sediment source fingerprinting approaches continue to be used in a variety of contexts and applications. For example, one study recently used a fingerprinting technique to examine the contribution of agricultural topsoils, damaged road verges and eroding channel banks to channel bed sediment collected in tributary sub-catchments of the River Wensum in the UK (Collins et al., 2013). Other studies have used such approaches to examine the efficacy of mitigation methods (Minella et al., 2008; Collins et al., 2010a). International debate on the need to continue refining fingerprinting procedures to try to tackle specific issues continues (e.g., Koiter et al., 2013; Walling, 2013). However, while sediment fingerprinting techniques are increasingly being used for a wide range of applications worldwide, the utility of this direct approach in quantifying sediment sources for evaluating the spatial provenance of sediment in larger river basins draining wildfire impacted landscapes has not been explored in detail. In fact, Smith et al. (2013) note that no existing published studies in wildfire basins provide estimates of sediment contributions from spatial sources defined in terms of burned and unburned areas. Existing work using fingerprinting in wildfire landscapes has tended to focus on assessing the changes in source types (e.g., surface versus bank erosion) post-wildfire and understanding process linkages driving such changes (e.g., Blake et al., 2006a; Owens et al., 2006; Wilkinson et al., 2009; Smith et al., 2011, 2012). The only previous work examining spatial units in a wildfire setting adopted a sediment budgeting approach based on fallout radionuclides (Blake et al., 2009b). Accordingly, the objective of this study was to apply a recently updated and revised sediment source tracing procedure incorporating uncertainty analysis (Collins et al., 2010a,b, 2012a) to quantify spatial source apportionment in a wildfire impacted river system in southern Alberta, Canada. The 2003 Lost Creek wildfire in southwest Alberta represented a particularly large and severe disturbance to a critical source water region that has shown little if any meaningful recovery of contaminant export (Silins et al., 2008, 2009; Bladon et al., 2008; Emelko et al., 2011; Allin et al., 2012). The present study explored contemporary spatial sediment source apportionment to assess the longevity of sediment export from wildfire and salvage logged landscapes.

2. Materials and methods

2.1. Site description

The study area is located in the Rocky Mountains immediately south of the Crowsnest Pass in southwestern Alberta, Canada. This region is characterized by Montane, sub-alpine and alpine ecological sub-regions with elevations spanning 1100–3100 m. Vegetation consists of mixed conifer forests dominated by lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) at lower elevations, sub-alpine forests at midelevations dominated by Engelmann spruce (*Picea engelmannii* Parry) and sub-alpine fir (*Abies lasiocarpa* [Hook.] Nutt). Alpine ecozones at higher elevations are characterized by alpine meadow vegetation and bare rock extending above the tree line. Regional geology is dominantly limestone, dolomite, shales, mudstones, and fine-grained sandstone, however the surface lithology is poorly coupled to bedrock geology because of late quaternary glacial history resulting in extensive deposition of calcareous glacial moraines, till blankets and till veneers. Regional annual precipitation varies from 700 to 1700 mm $year^{-1}$ (approximately 50% as snowfall), while streamflow ranges from 400 to 1300 mm $year^{-1}$ in the headwaters of this region. The flow regime is strongly snowmelt dominated with the annual melt freshet beginning in early May and peaking in early June with declining baseflow recession thereafter until the freeze-up in late October. The highest streamflows are typically observed in association with late spring rain-on-snow events (May–June) or in response to large convective or frontal storms in May–July. The high water production of this headwater region reflects very high annual precipitation combined with extremely high annual runoff ratios. Approximately 80% of the annual precipitation is routed as streamflow. Accordingly, this headwater region represents an important source water supply for downstream communities.

In 2003, the study area was directly impacted by the Lost Creek Fire which burned more than 21,000 ha in the Crowsnest Pass area. The wildfire burned as a near contiguous crown fire, consuming virtually all forest cover and forest floor organic matter across a large proportion of the headwater regions of both the Castle and Crowsnest rivers. Post-fire sediment export and yields have been monitored in a series of catchments (4–14 km^2) across the full range of flow regimes (spring melt, baseflow and stormflow) characteristic of this headwater region as part of the Southern Rockies Watershed Project (SRWP) since early 2004. The monitored data indicate substantial increases in sediment production from both burned watersheds and burned–salvage logged watersheds after the fire (salvage logging was conducted over a 1.5 year period after the fire). Three to four years after the fire, median sediment yields of burned watersheds were 11- and 31-times greater than those observed in unburned watersheds during the spring snowmelt period and during rainfall driven stormflows, respectively. Fifteen and 17-fold increases in sediment production were observed in salvage logged watersheds during these same flow periods (Silins et al., 2008, 2009). Unpublished data for 2012 indicates that sediment export and yields in disturbed watersheds are not yet showing any detectable recovery towards pre-burn conditions illustrating the severity and prolonged impact of this mass landscape disturbance on sediment redistribution. Because the 2003 Lost Creek wildfire occurred immediately upstream of the Oldman Dam, there is concern regarding continued sediment loading to the reservoir and the potential for associated water quality problems such as eutrophication on water supply. In the present study, sediment source tracing was conducted along a downstream gradient of the Crowsnest River to apportion primary sources of sediment efflux from forested sub-basins with contrasting levels of disturbance ranging from unburned reference areas in the headwaters, to both burned and burned–salvage logged areas further downstream (Fig. 1).

2.2. Sediment sample collection

A network of in situ time-integrating samplers was used to collect passively, composite samples of suspended solids (Phillips et al., 2000). This type of sampler is routinely used to collect a sufficiently large sample mass for laboratory analyses in source fingerprinting studies (Collins and Walling, 2006; Walling et al., 2006, 2008; Collins et al., 2010b). Critically,