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Wildfire impacts on stream sedimentation: re-visiting the Boulder Creek Burn in Little Granite Creek, Wyoming, USA

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Abstract In this study of a burned watershed in northwestern Wyoming, USA, sedimentation impacts following a moderately-sized fire (Boulder Creek burn, 2000) were evaluated against sediment loads estimated for the period prior to burning. Early observations of suspended sediment yield showed substantially elevated loads (5×) the first year post-fire (2001), followed by less elevated loads in 2002 and 2003, signalling a return to baseline values by 3 years post-fire. However, more recent work (8 years post-fire) has shown elevated suspended sediment yields that are more than double those predicted for the pre-burn range of flows. We tentatively attribute this increase to channel destabilization in the burned area due to the introduction of large wood from burned riparian zones and hillslopes. These results provide insight into the longer-term geomorphic impacts of wildfire that are associated with channel and bank instability in a burned riparian environment due, in part, to large wood dynamics.

Key words post-fire sediment yield; channel instability; instream large wood; Little Granite Creek; Wyoming, USA

INTRODUCTION

In August 2000, a 1400-ha (3500-acre) wildfire in the Gros Ventre Wilderness area near Bondurant, Wyoming, USA, burned substantial portions of the Boulder Creek watershed. Roughly 75% of the forested area in this watershed burned, 67% of which burned at moderate to high severity. The Boulder Creek watershed comprises 40% of the area within Little Granite Creek watershed where researchers from the US Geological Survey (USGS) and US Forest Service (USFS) had previously collected data on bedload and suspended sediment loads (Ryan & Emmett, 2002; Ryan & Dixon, 2008) between 1982 and 1997. The destruction of 1400-ha of old-growth forest in a wilderness area presented an opportunity to quantify increases in sediment loads associated with a wildfire relative to pre-burn baseline values. There are recognized limitations to this approach in that it assumes that the pre-disturbance data sufficiently characterize the flow and sediment regime for the watershed. Yet where adequate pre-disturbance data do exist, the magnitude of the hydrologic and sediment changes can be better quantified by placing flow and sedimentation rates into a broader context through comparisons with background rates (Shakesby & Doerr, 2006). In addition to sediment measurement, a series of monitoring reaches were established to quantify morphological impacts and large wood dynamics in the burned area, areas downstream of the burned area, and within an adjacent reference watershed (Ryan & Dwire, in review). Repeat surveys were used to quantify the changes in channel patterns and cross-sectional area for the first three years post-fire and later in 2007–2008, seven to eight years post-fire.

Results on changes in flow and sediment for the first three years post-fire are presented in Ryan *et al.* (2011). Those earlier observations showed that suspended sediment loads were substantially elevated (5×) the first year post-fire (2001), followed by less elevated loads in 2002 and 2003, suggesting a return to baseline values. In this paper, we present additional results derived from flow and sediment data collected in 2008 to: (a) estimate sediment yield eight years post-fire, and (b) determine whether earlier suppositions on recovery patterns were correct. We also present information on in-stream morphologic changes that are occurring (e.g. bank erosion), due, in part, to the influence of large wood dynamics in the burned riparian zone. Specifics on the dynamics of the large wood are addressed in a separate paper (Ryan & Dwire, in review).

Watershed description

Little Granite Creek (LGC), an upland contributor to the Snake River system, drains 54.6 km^2 (21.1 mi^2) of the Gros Ventre range south of Jackson, Wyoming, USA. The watershed is underlain by deformed sedimentary formations (sandstone and claystone formations of marine origin (Love & Christiansen, 1985) which are relatively unstable in areas. Over 100 active and inactive landslides have been mapped in the watershed, comprising about 20% of the total watershed area (WSGS & WRDS, 2001; refined by S. Ryan using field reconnaissance and aerial photographs). Prior to burning, forest cover was dominated by Lodgepole pine, classified as the persistent Lodgepole pine (*Pinus contorta*) community type, with different understory shrubs and graminoids (Steele *et al.*, 1983; Bradley *et al.*, 1992). In unconfined valley bottoms, riparian vegetation is primarily willow species (*Salix* spp.), with an extensive herbaceous understory (Youngblood *et al.*, 1985). In more confined portions, the flood plain overstory is composed of a mixture of Lodgepole pine, Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*), with riparian shrubs occurring along the stream banks (Youngblood *et al.*, 1985). Runoff is generated primarily by melting of the annual snowpack, with peak flow occurring between mid-May and mid-June. High, out of bank flows often last 1–2 weeks (USGS, 2007). Mean annual temperature is 1.0°C (33.3°F) and mean annual precipitation is 52.15 cm (20.53 in.) at a climate station in the vicinity of Bondurant (elevation 1982 m/6504 ft) (WRCC, 2005b). Most of the precipitation falls as snow from November through to March. Average annual snowfall measured at Bondurant between 1948 and 1999 was 340 cm, or 134 in. (standard deviation ±124 cm, or 48.9 in.) (WRCC, 2005a).

METHODS

Pre-fire suspended sediment samples and flow measurements were made during the course of 10 runoff seasons between 1982 and 1992 at a USGS gauging station at the confluence between Little Granite Creek and Granite Creek (Ryan & Emmett, 2002). Samples were collected by the USGS using depth-integrating samplers (e.g. DH-48; FISP, 2000). Post-fire flows and sediment transport were monitored at this same location in 2001, 2002 and 2003, and those methods and results are described fully in Ryan *et al.* (2011). While circumstances prevented re-establishing the complete suite of monitoring instruments that were used between 2001 and 2003, we were able to monitor turbidity and use this as a surrogate for suspended sediment concentration (SSC). The sensor (DTS-12 Turbidity Sensor^{TM}, Forestry Technology Systems) was deployed from 1 June to 15 September and turbidity was measured at 10-min intervals. A CR10x datalogger (Campbell Scientific) was used to log turbidity data. Intermittent grab samples (n = 23) were obtained during snowmelt runoff and baseflows using a DH-48 depth-integrating sampler, and these samples were used to calibrate the signal from the sensors and to develop SSC–discharge relationships. Flow stage was measured from 18 May to 15 September using an automated stage recorder (Aquarod^{TM}).

Laboratory analyses on the suspended sediment samples were conducted in accordance with standard USGS methods (Guy, 1969). The mass of material carried in suspension was determined by filtering samples through pre-processed filters, drying the content at 35°C for 2 h, then cooling, desiccating, and weighing the filters to determine the change in weight with added sediment. SSC data are expressed in mass per volume of water collected (mg L^{-1}).

DATA ANALYSIS

Runoff

Discharge estimates were obtained using a flow–stage rating curve developed previously for the site (Ryan & Dixon, 2008). Comparisons between readings from an on-site staff plate and data from the stage-recorders were comparable to the previous period, indicating that the flow-stage rating curve had not shifted and was valid for this purpose. Mean daily flows were calculated as an average of the equally timed measurements for each 24-h period. Since the stage recorders were operational only part of the year, an estimation of flow for the ungauged, early season period was needed. A regression model was developed for this purpose using the available partial year record and data from a nearby gauge (USGS 13023000: Greys River above reservoir near Alpine, Wyoming). Flow estimates from the regression analysis were then used to estimate mean daily flow for the critical data gap (18 May–1 June).

Suspended sediment yield

An estimate of annual suspended sediment yield was made using turbidity–SSC–discharge relationships. Because there were no turbidity measurements obtained prior to 1 June, similar measurements collected in 2003 were used to develop an improved regression between turbidity and SSC. The data from 2008 and 2003 largely overlapped, indicating similarity in the relationship and justifying the incorporation of 2003 data into the model. Moreover, the inclusion of the 2003 data improved the stability of the model, particularly for higher discharges. A least-squares, non-linear regression model was developed between SSC and the corresponding turbidity value:

$$SSC_i = 1.64t^{1.05}$$

where SSC_i is the estimate of instantaneous SSC (in mg L^{-1}) and t is the observed turbidity value (in NTU) ($r^2 = 0.98$). For the period prior to installation of the turbidity sensor, a second model was developed using SSC measurements and discharge Q ($r^2 = 0.89$):

$$SSC_i = 1.45e^{0.0259Q}$$

There is greater uncertainty in the estimates of SSC from this model because sediment concentrations are influenced by fluctuations in supply as well as changing flow (Ryan & Dixon, 2008). However, it does provide an estimate of SSC for the unmeasured period (15 May–1 June), and therefore the estimate of annual sediment yield is not unreasonably low due to data gaps that would be calculated as zero values. The SSC estimates were then multiplied by flow estimates obtained from the stage–discharge relationship. Values from each 24-h period were then averaged to obtain mean daily sediment yield (t d^{-1}) for each day of monitoring during snowmelt and base-flow. These daily values were summed to approximate annual suspended sediment yield (t). While only a portion of the annual runoff was monitored, the majority of sediment is transported during this period of high flow and so most of the total load is accounted for in this series of calculations.

Estimates of erosion, sediment volume and sediment yields from channel banks

Areas of substantial bank erosion, lateral channel migration and avulsions in burned reaches were identified from channel surveys using differences in mapped areas between the 2003 and 2007 or 2008 surveys. Given the composite nature of the channel banks (primarily silt and fine sand over a gravel/cobble base), we assume that most eroded bank material would be moved in suspension, rather than as bedload. Sediment volume was estimated by multiplying eroded area by mean bank height, computed as the difference between the long profile near the eroded bank and banktop. The estimated volumes from each erosional area were summed and averaged for the six burned reaches (including two reaches with negligible bank erosion). Assuming a bulk density of 1 to 1.25 g cm^{-3}, the mass of sediment per unit channel length was calculated and extrapolated over the total length of channel in the burned area to predict the total sediment yield from bank erosion and channel avulsion. This value was divided by 4 to account for the fact that the onset of bank erosion may have started as early as 2003. The estimate of annual sediment yield from bank erosion in the burned area was then compared to the estimated annual suspended sediment yield for 2008.

RESULTS

Runoff

Snowpack and discharges measured between 2001 and 2003 were low, with the highest flows having calculated return frequencies of 1.4 to 1.5 years (bankfull or slightly less). These occurred for 2 days during the entire 3 year period (Ryan *et al.*, 2011). By comparison, discharge measured

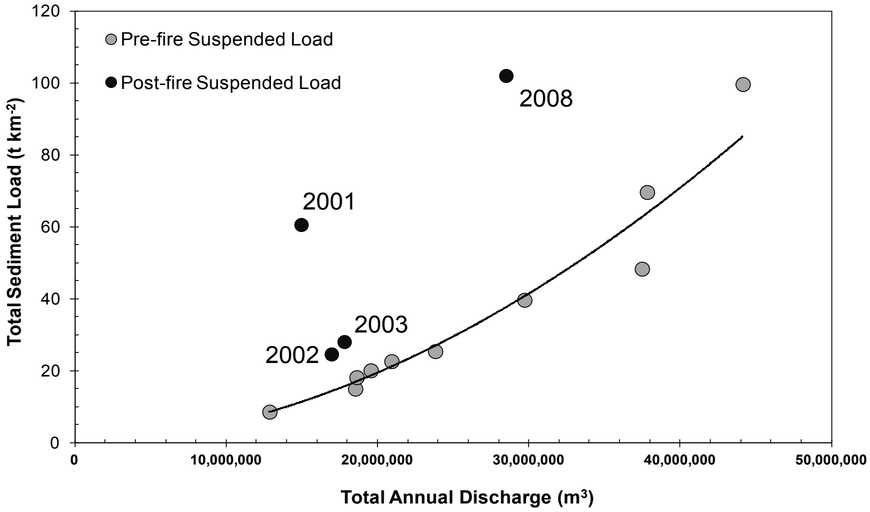

Fig. 1 Annual suspended sediment loads estimated for pre-burn and post-burn periods. Line is fit only to pre-burn data. Values for 2008 may be low as these represent only a partial year estimate (May–September).

in 2008 was relatively high, with out of bank discharges lasting 5 days during the primary peak and a second peak of near bankfull discharges lasting for about a week. Estimated return frequency for peak discharge in 2008 was 2.5 to 3 years. Total daily runoff was summed for the period of observation to approximate annual runoff (Fig. 1). Based on comparisons with the Greys River gauge, we estimate that this accounts for 85% of the total annual flow in 2008 at Little Granite Creek. The estimate of partial annual flow in 2008 was among the highest flows measured at this site.

Estimates of annual suspended sediment load

Suspended sediment loads calculated for 2008 were elevated substantially relative to pre-burn baseline values (Fig. 1). The expected value for the given discharge was 40 t km^{-2} while the calculated value was over 100 t km^{-2}, more than double the pre-burn suspended sediment load. As a caveat, there is some unknown degree of uncertainty in the 2008 estimate, given the limited number of samples collected and restricted period during which the turbidity sensor was deployed. The uncertainty increases for higher flows where the estimate is from the SSC–discharge relationship and no physical samples were obtained. Nevertheless, the models that were used do generate a reasonable approximation of the suspended sediment concentrations for the range of measured calibration samples.

Bank erosion estimates

Between 2003 and 2007, the number of pieces of large wood increased from 303 to 526 in the reaches within the Boulder Creek burn area (mean number of pieces per site increased from 51 to 88). Observed changes in channel form attributed to increased wood input include: (a) channel avulsions; (b) erosion of banks and terraces where wood re-directed flow into the bank; and (c) multiple new sources of fine sediment due to bank instability (Ryan & Dwire, in review). It was postulated that increased channel instability contributed to increased sediment loads measured downstream. Estimates of the volumes of channel bank erosion determined from the mapped areas indicated some between-site variability, but on average, about 12 m^3 of primarily fine sediment was contributed per 100-m sampled reach (Fig. 2). Based on these measurements extrapolated over 12.7 km of stream in the burned area, an estimated 468 t of material may have been available for transport in suspension, annually, from the burned area due to just bank erosion as a sediment

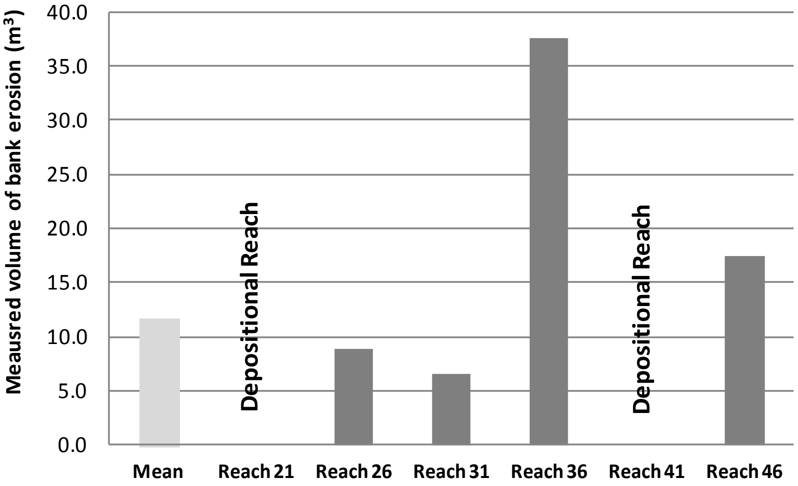

Fig. 2 Measured volume of sediment eroded from channel banks within the burned reaches of Boulder Creek between 2003 and 2007/08.

source. This would account for 15 to 54% of the estimated increase in suspended sediment observed in 2008, depending on whether the erosion occurred evenly over the 4 year timeframe or primarily during the high flow event in 2008.

CONCLUSIONS

This series of observations of increased sediment loads occurring eight years after the Boulder Creek burn in Little Granite Creek watershed suggest that the system is still responding to the large-scale forest disturbance. Calculated annual suspended sediment load was more than double the estimates obtained from the pre-burn period, and proportionally greater than the loads from 2002 and 2003 for the given level of discharge. Although not explicitly addressed in this analysis, we tentatively attribute a portion of these increases to channel destabilization in the burned area, in association with the introduction of large wood from burned riparian areas and hillslopes. This relationship is explained more fully in a separate paper (Ryan & Dwire, in review), but repeat surveys of channel form and large wood distributions show increased bank and bed instability in burned reaches coincident with increased loading of large wood. Estimates of channel bank erosion indicate that up to half of the sediment may be contributed to the annual load from this source. While there is some uncertainty in the estimates of sediment loads and erosion rates, these results provide insight into the longer-term geomorphic impacts of wildfire that are associated with large wood dynamics and changes to channel and bank stability in the burned riparian environment.

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