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The effect of in-stream wood structures on fine sediment storage in headwater streams of the Canadian Rocky Mountains

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Abstract The recruitment of wood from channel margins to headwater streams can profoundly influence stream hydrology, morphology, ecology and sediment transport dynamics (erosion and deposition). This study examines the effect of in-stream wood deposits on pool formation and fine sediment storage in two headwater streams with contrasting land disturbance on the eastern slopes of the Canadian Rocky Mountains. Six representative study reaches, three from each disturbance type (burned/salvage logged *vs* recreation/grazing) were selected to examine pool spacing, pool type and fine sediment storage. A total of 94 and 66 in-stream wood structures were found in the Lyons East (LE) and Corolla Creek (CC) study areas. The frequency of in-stream wood structures was 1.5/100 m (LE) and 1.48/100 m (CC). Overall, the volume of fine sediment stored in pools was greater in burned-salvage logged reaches (Lyons East) compared to unburned (reference) reaches of Corolla Creek. The increased volume of fine sediment is related to increased sediment availability due to mass wasting processes and overland flow caused by wildfire.

Key words in-stream wood; dams; jams; fine sediment; gravel bed rivers; wildfire; watershed disturbance; Canadian Rocky Mountains

INTRODUCTION

Forested watersheds in western North America provide a wide range of ecosystem services and are critical source regions for the drinking water supply of more than 180 million people (Hauer *et al*., 2007; Emelko *et al*., 2010). The effects of landscape disturbance (recreation, logging, wildfire, agriculture) on the morphology and ecological integrity of streams draining forested landscapes (Fetherston *et al*., 1995; Gurnell *et al*., 1995; Whol & Jaeger, 2009) are well documented. Wildfire can accelerate the rates and magnitudes of terrestrial erosion and sediment loading into fire affected watersheds (DeBano *et al*., 1998; Silins *et al*., 2009), which along with increased wood recruitment from burned channel margins can lead to in-stream wood structures that often produce secondary effects of wildfire on stream morphology, ecology and sediment transport dynamics (Beschta & Platts, 1986; Nakamura *et al*., 2000). The input of wood to streams also changes channel bed roughness, which can dissipate stream energy and promote sediment deposition upstream of the obstruction (Bilby & Ward, 1989; Trotter, 1990; Curran & Wohl, 2003; Webb & Erskine, 2003; Gurnell *et al*., 2005).

Various forms of in-stream wood structures, such as dams and jams, influence the amount and type of sediment stored in the host channel (Jackson & Strum, 2002; May & Gresswell, 2003). Fine sediment (clay, silt, fine sand) is typically stored in the void spaces of natural gravel bed rivers (Collins & Walling, 2007). When the supply of sediment exceeds the storage capacity of the gravel bed, continued fine sediment deposition causes surficial layers or drapes to form in pools during conditions of low flow (Lisle & Hilton, 1999). According to the work of Lisle & Hilton (1992), the fraction of pool volume filled with fine sediment can be used as an index of the supply of mobile sediment. They define this fraction (V*) as the ratio of fine sediment to pool water volume plus fine-sediment volume. V* has been used as an index of the supply of mobile sediment in the stream channel (Lisle & Hilton, 1992) as well as an indicator of habitat suitability for aquatic organisms (Hilton & Lisle, 1993). Although this approach has been used to study the effects of wildfire on fine sediment storage in Wyoming streams (Zelt & Wohl, 2004), no comparable studies have been conducted in wildfire impacted landscapes in the Canadian Rockies. Such information is required to evaluate and compare the longer term, secondary effects of wildfire on fine sediment storage in gravel bed streams which, in turn, has implications for water quality and habitat suitability and sediment sources. The objective of this study was therefore to examine the effect of in-stream wood structures on fine sediment storage in two catchments of varying land disturbance types (burned *vs* unburned reference) that are located in the headwater regions of the eastern slopes of the Canadian Rocky Mountains.

METHODS

The study was conducted in two headwater catchments of the Oldman River Basin (Lyons East 49°34′08.5″N, 114°27′19.4″W, and Corolla Creek 49°25′30.6″N, 114°23′26.8″W) located in southwest Alberta. The two catchments are located in close proximity to one another (~10 km) and are situated in similar hydro-climatic and physiographic settings just east of the continental divide along the Flathead range. Mean annual precipitation is approximately 850 mm/year for both catchments. The drainage area and perimeter of the study watersheds are comparable but Lyons East has a larger average channel and catchment slope (Table 1). The studied streams in both catchments are classified as third order channels. Lyons East (LE) was initially disturbed by wildfire in 2003, then subsequently post-fire salvage logged (82% burned, 24% of which was salvage logged; no logging occurred within 30 m of the stream). Corolla Creek (CC) is an unburned reference watershed. Soils in the study catchments include thin gray luvisol and brunisol soils, which influence the type of vegetation in this mountain eco-region (Bladon *et al.*, 2008; Oldman Watershed Council, 2010).

Table 1 Physical characteristics of the study catchments.

Study basin	Drainage area (km^2)	Perimeter (km)	Mean elevation (m) (Range)	Catchment slope (%)	Channel slope
Burned	13.06	17.2	1683 (1441–2028)	31.4	0.04
Reference	13.15	20.3	1568 (1429-1963)	11.4	0.028

An initial survey was conducted using GPS to identify the location, type and frequency of all in-stream wood structures in the study basins. Three representative in-stream wood structures (Fig. 1) were identified in each study catchment. Detailed surveys were conducted to classify wood structure type and morphological properties. Pool type was classified according to the formation mechanism (self-forming or forced) and channel processes (scouring or damming) using the methods of Hawkins *et al.* (1993) and Montgomery *et al.* (1995). Pool dimensions (length, width and depth) were determined using the methods outlined by Hilton & Lisle (1993). Pool volume was calculated by measuring water depth at a minimum of 10 locations across each pool, and the number of transects surveyed varied among pools as a function of pool length. Typically, transects were located 1 m apart for longer pools and 0.5 m apart for shorter pools.

The relative volume of fine sediment in pools (V*) was described as the fraction of scoured pool volume occupied by fine sediment (Lisle & Hilton, 1992). Measurements of water depth, sediment surface depth and fine sediment depth were made at a minimum of 10 intervals across each pool transect using a steel metre stick with an accuracy of 0.1 cm. An abrupt change in resistance to the rod as it passed from sand or fine gravel to packed coarse gravel and cobbles indicated the base of the residual pool. The weighted average (V_w^*) of all pools in each study reach was calculated using the following equation.

$$V_w^* = \sum(\text{residual fines volume})/\sum(\text{scoured residual pool volume}) \qquad (1)$$

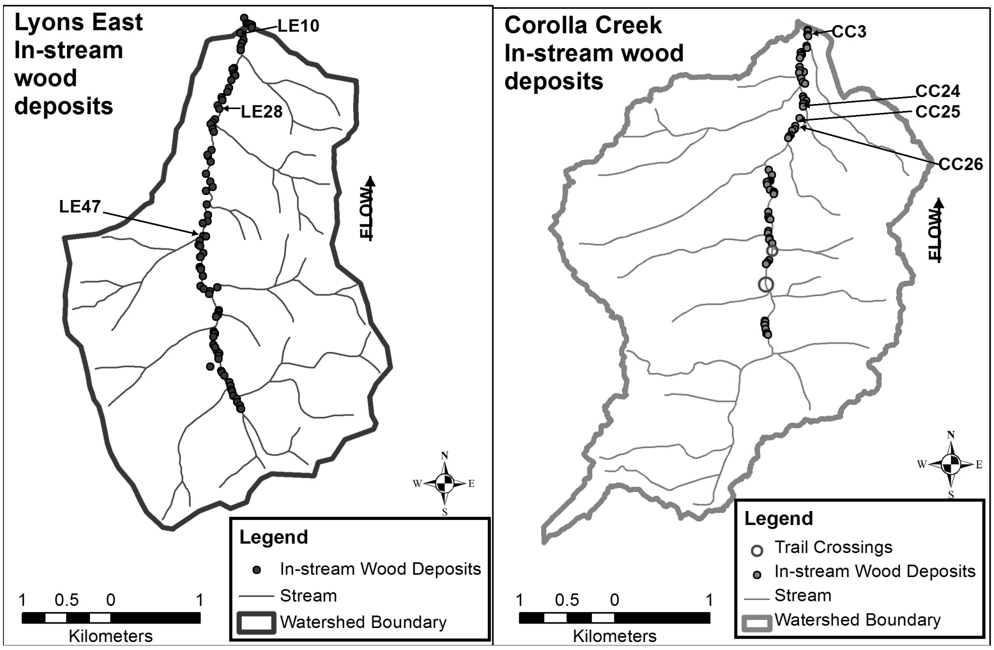

Fig. 1 Location of all in-stream wood structures and detailed study sites in Lyons East and Corolla study catchments.

RESULTS AND DISCUSSION

Wood structures and pool morphology

The location of all in-stream wood structures and detailed study sites (LE10, LE28, LE47) (CC3, CC24, CC26) are shown in Fig. 1. A total of 94 and 66 in-stream wood deposits that included jams, partial jams and dams were identified (Table 2). Although there was a difference in the total number of in-stream wood structures, the frequency of in-stream wood deposits was estimated at 1.5/100 m (LE) and 1.48/100 m (CC). This estimate is comparable to the work of Zelt & Wohl (2004). They reported frequencies of 1.6 and 1.5 debris jams/100 m in burned and reference catchments, respectively. For comparison, Wohl & Jaeger (2009) reported fewer than 2 jams/100 m in a study conducted on the Colorado Front Range.

In-stream wood can have a profound effect on channel morphology and pool formation (Kreutzweiser *et al.*, 2005). Previous studies describe a relationship between wood loading and pool spacing in plane bed, pool-riffle and forced pool-riffle channels (Montgomery *et al.*, 1995; Abbe & Montgomery, 1996). In a typical free-formed pool-riffle stream, pools are spaced approximately five to seven channel widths apart (Leopold *et al.*, 1964) compared to one to four channel widths typical of step-pool channel forms (Montgomery & Buffington, 1997). In the current study, pool spacing ranged from 1.53 to 2.31 channel widths (Table 3) which is less than expected for the pool-riffle streams we studied, and at the lower end for streams with step-pool morphology.

Table 2 Number and frequency of in-stream wood structures.

Wood structure	Burned count	Burned frequency (/100 m)	Reference count	Reference frequency (/100 m)
Single	10	0.16	9	0.2
Partial jam	18	0.29	13	0.29
Jam	40	0.64	31	0.7
Dam	26	0.41	13	0.29
Total	94	1.5	66	1.48

Table 3 Summary of reach-average channel characteristics.

Channel characteristic	Symbol	LE10	LE28	LE47	CC3	CC24	CC26
Bankfull width (m)	W_{bf}	13.22	10.23	12.99	12.67	12.95	14.73
Gradient (m/m)	S_w	0.03	0.02	0.02	0.02	0.02	0.03
Forced Pools (%)	F%	67	60	67	20	33	100
Forced pools – wood-affected (%)	F_{wa}%	50	20	33	20	33	33
Pool length (m)	PL_m	37	25	13	43	11	17
Pool length (channel widths)	PL	2.8	2.44	1	3.39	0.85	1.15
Pool spacing (m)	SP_m	20	20	30	21	29	31
Pool spacing (channel widths)	SP	1.53	1.97	2.31	1.63	2.24	2.1
% reach length in pools	P%	30	24	14	42	12	19
Mean residual pool depth (cm)	D_r	10.6	7.3	13.2	12.5	14	18.9
Mean residual volume per pool (m^3)	V_r	1.21	1.27	1.64	2.95	3.34	3.99

Table 4 Residual pool and fine sediment volume.

Site	Pool #	Location	Pool type	Residual pool volume (m^3)	Residual sediment volume (m^3)	V*
LE10	1	US	Lateral scour	1.094	0.002	0.001
	2	US	Mid-channel	1.291	0.004	0.003
	3	At wood	Plunge	0.49	None	
	4	At wood	Deflector	1.699	0.016	0.01
	5	At wood	Underflow	1.361	0.006	0.004
	6	DS	Plunge	1.294	0.006	0.005
LE28	1	US	Plunge	0.472	None	
	2	US	Mid-channel	0.754	None	
	3	US	Lateral scour	0.466	None	
	4	At wood	Deflector	4.43	0.379	0.085
	5	DS	Plunge	0.239	None	
LE47	1	US	Lateral scour	1.241	0.042	0.033
	2	At wood	Underflow	3.1	0.049	0.016
	3	DS	Lateral scour	0.588	0.002	0.004
CC3	1	US	Trench	1.413	None	
	2	US	Trench	3.542	None	
	3	At wood	Dam	1.844	None	
	4	DS	Mid-channel	3.171	None	
	5	DS	Trench	4.785	None	
CC24	1	At wood	Underflow	3.729	0.017	0.004
	2	Between	Lateral scour	1.229	None	
	3	DS	Mid-channel	5.063	0.154	0.03
CC26	1	US	Deflector	0.014	None	
	2	At wood	Deflector	6.213	0.011	0.002
	3	DS	Trench	5.73	None	

Wood structure played a key role in pool characteristics in each of the six study reaches (Table 4). In half of the study reaches (LE28, LE47 and CC26), the highest pool volumes were found at in-stream wood structures. The wood-affected pool volume was approximately 50 to 70% of the total pool volume compared to 12.5 to 52% in Corolla Creek.

Fine sediment storage

The presence of wood structures was also closely associated with residual volume of fine sediment (V*) measured in pools (Table 4). With the exception of site CC3, fine sediment deposits were consistently observed at pools created by in-stream wood structures. The largest residual fine sediment deposit was measured at the inlet of pool 3 (site CC24) which had experienced considerable bank failure in the reach immediately upstream. The second largest deposits of residual fine sediment were located in the middle and upper reaches of Lyons East Creek (sites LE28 and LE47). Residual deposits of fine sediment were also observed at sites CC3 and CC26. With the exception of a plunge pool (LE10–pool 3), the highest volume of fine sediment storage occurred at wood-affected pools in Lyons East Creek. Accordingly, the majority (5 out of 8) of wood-affected pools were found to store more fine sediment than in non-wood-affected pools.

The weighted average relative volume of fine sediment in pools (V^*_w) was also affected by wildfire (Table 5). Zelt & Wohl (2004) reported an average residual pool fine sediment volume (V^*_w) of 0.17 and 0.23 for reference and burned streams, respectively. In the present study, V^*_w ranged from 0.005 to 0.056 in burned, and 0 to 0.017 in unburned streams. While V^*_w was highly variable between in-stream wood structures, it was more pronounced in Lyons East Creek indicating a higher presence of stored sediment in the stream affected by wildfire disturbance.

In the current study, the average sediment depth in pools ranged from <0.1 to 0.7cm and from <0.1 to 0.3cm in Lyons East and Corolla Creeks, respectively. The presence of more sediment is likely related to the effect of land disturbance by wildfire on sediment source, availability and conveyance processes. Based on field observations, sediment supply to the channel was more pronounced due to vegetation loss and its impact on overland flow hillslope/bank failure. Previous research on in-stream wood and associated fine-grained sediment storage reported thicker but less frequent deposits within disturbed watersheds (Zelt & Wohl, 2004). Approximately 64% of the pools burned streams contained deposits of fine sediment compared to 36% of the pools in reference streams.

Table 5 Weighted average of V* for selected study reaches.

Disturbance	Site	V^*_w	n
Burned	LE10	0.005	6
	LE28	0.056	5
	LE47	0.019	3
Reference	CC3	0	5
	CC24	0.017	3
	CC26	0.001	3

CONCLUSION

The volume of fine sediment deposits was evaluated in pools of gravel bed streams draining two study catchments with contrasting landscape disturbance. The sediment deposits were generally thicker and more prevalent in pools of the wildfire impacted stream compared to the reference stream. The lack of sediment in Corolla Creek was likely also related to the greater presence of bedrock in the channel, which limited the sediment supply. The results suggest that pools located at in-stream wood deposits represent an important sink for fine sediment in highly disturbed headwater streams on the eastern slopes of the Canadian Rocky Mountains, which may impact local and downstream water quality and aquatic habitats.

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